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SPEED CONTROL OF INDUCTION MOTORS

by

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INTRODUCTION

The polyphase induction motor is inherently a constant speed motor. While its operating characteristics are similar to those of the direct current motor of the shunt type, the induction motor is not as adaptable for adjustable speed as the former. Therefore, where variable speed motors have been required to a large extent, as for tool machine drive, shunt type motors have been installed, the power in the form of direct current either being generated directly or converted by a converter or motor generator where alternating current was available. Due to the almost universal distribution of electric power by alternating current because of the ease of its generation and transmission, there has developed an increased demand for induction motors with adjustable speed control. The work done along this line has resulted in the development of several methods which require for their operation either one or two induction motors. These methods may be classified as follows:-

A. With one induction motor

1. Rheostatic control
2. Separate sets of windings (Multi-speed windings)
3. Internal concatenation
4. Spinner speed control

B. With two or more machines

1. Concatenation or cascade connection
2. Concatenation with multi-speed windings

3. Dynamic control

- a. By rotary converter and motor generator
- b. Auxiliary induction driving motor

The speed of an induction motor depends upon three important factors, (1) frequency, (2) poles per phase, and (3) the slip. The synchronous speed or the speed of the rotating flux of a polyphase motor is represented by the equation

$$S = \frac{60 \times f}{p/2}$$

where S is the synchronous speed in R. P. M., f is the frequency in cycles per second, and p is the number of poles per phase.

The speed of the motor when operating under a load is $N = S (100\% - s)$ where N is the speed in R. P. M., S is the synchronous speed, and s is the slip in per cent of synchronous speed.

In all the methods previously classified and hereinafter described, the object, in order to obtain various speeds, is to change one or two of the following:- the slip, the frequency, the number of poles, or the factors controlling them. The various methods, which are used to bring about these changes, will be described somewhat briefly, although not exactly as in the order given. The internal concatenation and Spinner speed control methods will be described after cascade connection of two induction motors.

Rheostatic Control

When an induction motor is operated with a negligible resistance in the secondary circuit it is inherently a constant speed machine. If a variable resistance be connected into the secondary circuit it becomes possible to change the speed of a motor operating under constant load by altering the resistance. The speed will be inversely proportional to the copper loss in the secondary circuit. As long as the load and this resistance remains constant the speed will remain constant but any reduction in either load or resistance will increase the speed. With a constant load and within a limited range this method is suitable as far as speed control is concerned but is objectionable on account of the large $I^2 R$ losses in the controlling resistance which renders the efficiency low. On the other hand if the load is variable, rheostatic control is wholly impracticable because the speed will not remain constant under a change in load. These two objections therefore greatly limit the use of rheostatic control.

Multi-speed Windings

Since the speed of the ordinary induction motor depends on the frequency and the number of poles, several definite constant speeds may be obtained by placing two or more separate and distinct windings on the stator, each winding providing for a different number of poles. To introduce more than two separate windings, however, leads to too great complications in the connections. Each winding may be rearranged, however, to give different numbers of poles so that by using two windings three

or four definite speeds may be obtained. This method is the most satisfactory as regards efficiency and speed regulation. Its disadvantages are that it must be disconnected from the line when changing the speed, and the speed is not varied gradually. If a wound rotor is used intermediate speeds may be obtained but always subject to the disadvantages mentioned under rheostatic control.

Concatenation or Cascade Control

This method involves the use of two machines whose rotors are mechanically connected. By this means two or more definite constant speeds may be obtained. If two similar machines having the same number of poles be mechanically connected together and if the primary of one be connected to the line and the secondary connected to the primary of the second machine, the secondary of which is short circuited, as shown in figure 1, the set will run at half synchronous speed. This can be shown mathematically as follows: The speed of the first machine will be $1 - S$, where S is the slip. The speed of the second machine will equal the slip of the first or will be S . Since the rotors are mechanically connected their speeds are equal. Therefore

$$\begin{aligned} 1 - S &= S \\ \text{or} \quad 2S &= 1 \\ S &= \frac{1}{2} \end{aligned}$$

In general the speed of two machines so connected is given by the following equation:

$$\text{Speed R. P. M.} = \frac{f \times 120}{P_1 \pm P_2}$$

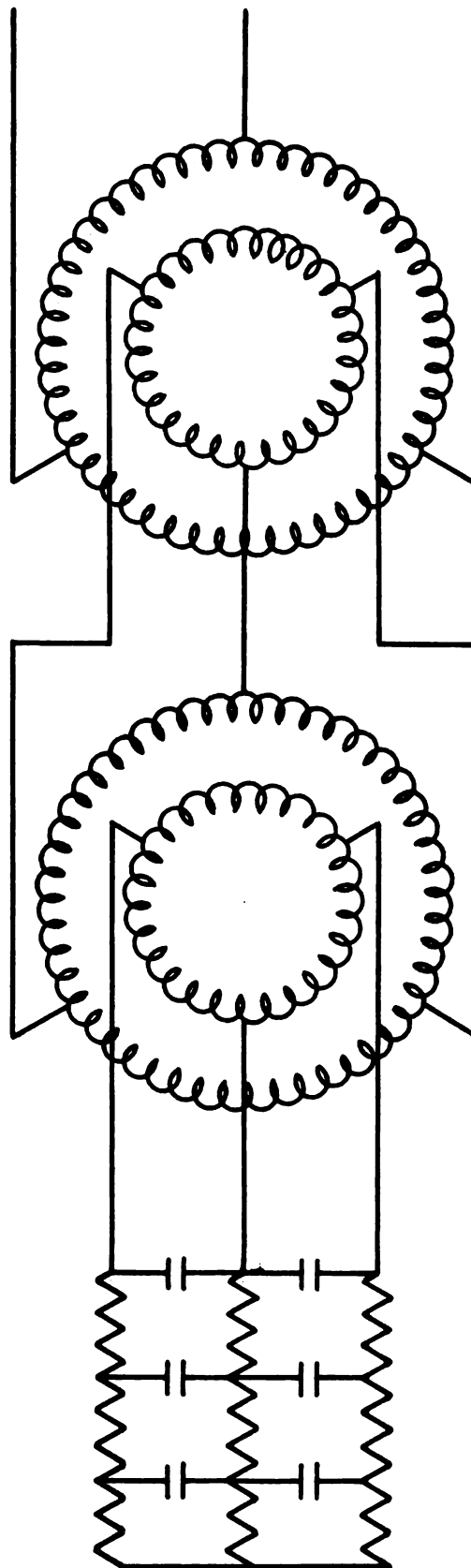


FIG. 1.

Where f is the frequency, P_1 is the number of poles on the first machine, and P_2 the number of poles on the second machine. The plus or minus sign denoting whether the machines are connected so that the two rotors tend to run in the same direction or in opposite directions. The first is called direct concatenation; the second, differential concatenation. Thus with two machines having different numbers of poles, four different speeds may be obtained. Two speeds are obtained by using either motor separately and the other by connecting in direct or differential concatenation.

The characteristics of the combination are similar to those for a single machine. The efficiency is less, however, since now the losses of the two machines must be supplied. Considerably more floor space is also required per horsepower output since the two machines running at half speed furnish the same output as one machine running at full speed.

The results obtained by connecting two motors in concatenation can be obtained in a single machine by arranging two separate superimposed windings on the stator and on the rotor. The two windings on stator and rotor are so connected that the magnetic effects produced are similar to those produced in the two separate machines. Thus the single machine can be made to revolve at half synchronous speed. An improvement on this method consists in so arranging a single winding on stator or rotor that the same results are accomplished as with the use of two separate windings. This results in a reduced copper loss and higher efficiency.

Spinner Speed Control

Another unique method of speed control is known as the Spinner method. An idea of its construction may be obtained if we imagine a drum, capable of revolving about the rotor axis, to be inserted between the rotor and stator of an induction motor with the air gap made large enough to accommodate the drum. Upon the inner surface of this drum is a winding connected to slip rings. This winding forms the primary for the rotor. Upon the outer surface is an ordinary squirrel cage winding. The drum or spinner can be held stationary by a brake band.

For the sake of illustration we will assume that the stator has twelve poles and the primary winding on the spinner is wound for six poles. If the spinner is held stationary and a 60-cycle current be applied to the slip rings a speed of 1200 R. P. M. will be obtained. If the spinner is released and a current is applied to the stator, a speed of $1200 + 600$ or 1800 R. P. M. will be obtained if the rotating field of spinner and stator revolve in the same direction. If they revolve in opposite directions a speed of $1200 - 600$ or 600 R. P. M. will be obtained. Thus there are three definite speeds available.

This machine is obviously more massive and more costly in construction than the ordinary induction motor.

Another method employing this same principle consists in using an auxiliary motor whose rotor is belted or geared to the stator of the main motor. This stator is built to revolve in the same way as the spinner in the preceding description.

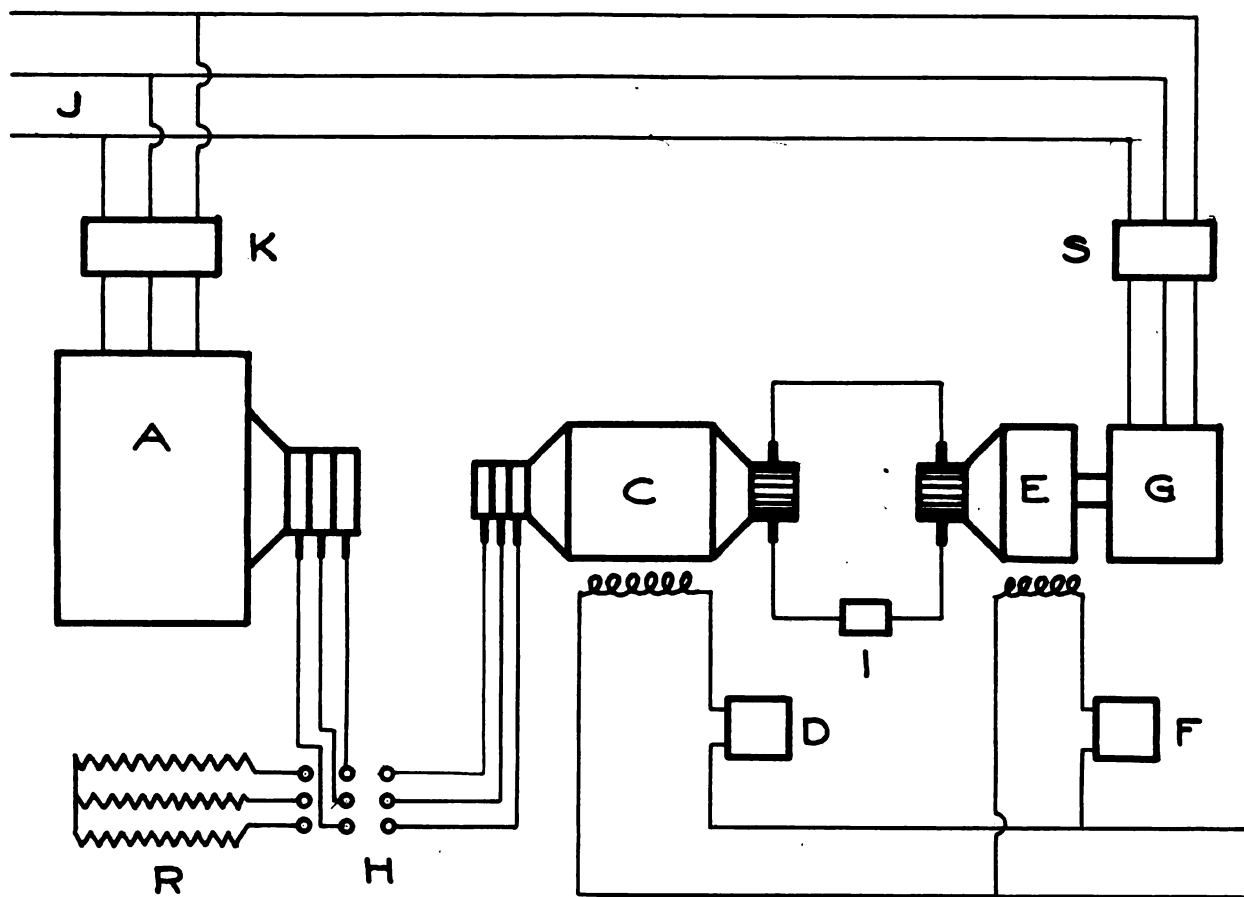


FIG. 2.

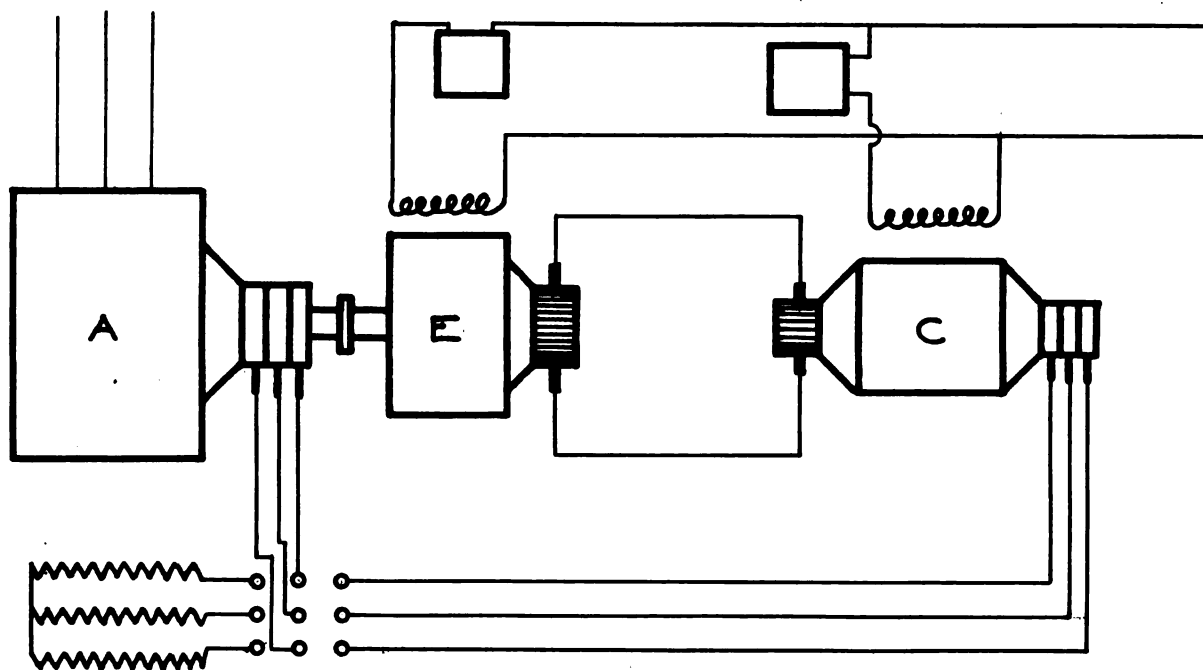


FIG. 3.

In this particular machine as actually built, pole changing arrangements were used on both main and auxiliary motors, and a range of eighteen different speeds were obtained ranging from 1000 R. P. M. to 3500 R. P. M. By employing a wound rotor with a pole changing device to obtain the different numbers of poles corresponding to those on the stator it would be possible to change gradually from one speed to the next by making use of the method of rheostatic control.

This machine is too complicated and costly in construction to have come into general use.

Dynamic Control

Another arrangement has been tried out which gives very satisfactory speed control. It involves the use of an induction motor, a rotary converter and a motor generator set. The speed can be adjusted to any desired value and maintained constant regardless of the load. Only standard machines are used so that no new difficulties are encountered in repair or in operation.

The manner in which these machines are connected is shown in figure 2 on the opposite page. "A" is an ordinary three phase induction motor having a wound rotor, "C" is a three phase rotary converter connected, as shown, to the slip rings of the induction motor. The direct current side of the rotary converter is connected to the direct current motor "E". "G" is a squirrel cage induction motor which operates as an induction generator after the apparatus has been placed in operation. Both converter and direct current motor are separately excited.

In starting, the switch "H" is thrown over connecting the rotor to the resistance "R". At the same time the switch "S" is closed which starts the motor generator set. Normal field is placed on the rotary converter and the field of the direct current motor is reduced to zero. The switch "H" is now thrown over connecting the rotor to the rotary converter. Since the induction motor is operating under no load its slip is very small, consequently the secondary frequency will be low, and the converter will rotate slowly. The switch "I" is closed last. The speed may now be controlled by adjusting the field of motor "E". As the field of "E" is slowly increased from zero, the e.m.f. generated will increase. Since this e.m.f. is impressed on the rotary converter its speed will increase. Therefore the frequency on the alternating current side must increase. Since the rotary converter and the rotor of the induction motor must operate in synchronism it is evident that the rotor must decrease in speed.

The above arrangement is satisfactory where the torque remains constant regardless of a change in speed. If the torque increases with the speed a modified arrangement is used to secure a constant horsepower output.

The connections are shown in figure 3. It will be seen that the induction generator is not used but the motor "E" is connected directly to the rotor shaft of the induction motor. The motor is started on the resistance "R" and after coming up to speed is connected to the rotary converter. A change in speed is accomplished in exactly the same manner as before, namely,

by varying the field on "E". In this case, however, since the speed of "E" varies, it must have a series winding having a considerable over compounding to make up for the drop in the armature voltage. If the speed of the induction motor starts to decrease due to an increase in load a heavier current will flow in the secondary circuit and its frequency will be increased. This will cause the rotary converter to increase in speed resulting in a higher impressed voltage on the motor "E". It then supplies power mechanically to the motor thus keeping up its speed.

Of all the methods of speed control which have been described it is evident that none of them compare very favorably with the direct current motor. In every case either efficiency or simplicity of construction and operation must be sacrificed to gain the desired end. And even then it is only imperfectly realized.

The foregoing has been a brief explanation of most of the methods which have been used. The following will be taken up in explaining a new idea which apparently has not been tried and which it was hoped would give a satisfactory method of speed control. The scheme is somewhat analogous to rheostatic control except that the external resistance in the secondary circuit is replaced by a counter electromotive force. This will eliminate the most objectionable feature of rheostatic control, namely the large copper losses in the secondary circuit. This e.m.f. is to be supplied by a second similar machine which may or may not be mechanically connected to the first. The secondaries of the two

machines are connected together and the primary of one of the machines is connected directly to the line while the primary of the other is connected to the line through an induction regulator. Thus a means is provided for varying the voltage on the second machine. With zero voltage impressed on the second machine the secondary of the first machine is practically shunted through a circuit of low resistance. Consequently it will run at a speed only slightly below synchronism. If a voltage be impressed on the primary of machine No. 2 a voltage will be induced in the rotor which will oppose the voltage in the rotor of the first machine, if the rotors are so connected mechanically that the voltages are in phase opposition. It was thought that this opposing voltage could be made of such a value that it would reduce the voltage in the first machine thus cutting down the current and causing an increase in the slip.

The machines used in the experimental work were two 3-phase, 5 horsepower, 60-cycle, 6 pole induction motors, having a synchronous speed of 1200 R.P.M. The rated primary current at 110 volts was 52.4 amperes and the secondary current 22.5 amperes. These two machines were connected up as shown in figure 4. The voltage regulator used was rated at 110 volts and could vary the voltage by plus or minus 20 per cent.

The first step in the experimental work was to ascertain the relative position of the rotors at which their voltages would be in phase opposition. This was done by placing a voltmeter in the secondary circuit and taking readings of volts and mechanical degrees shift of the two rotors. Equal voltages were im-

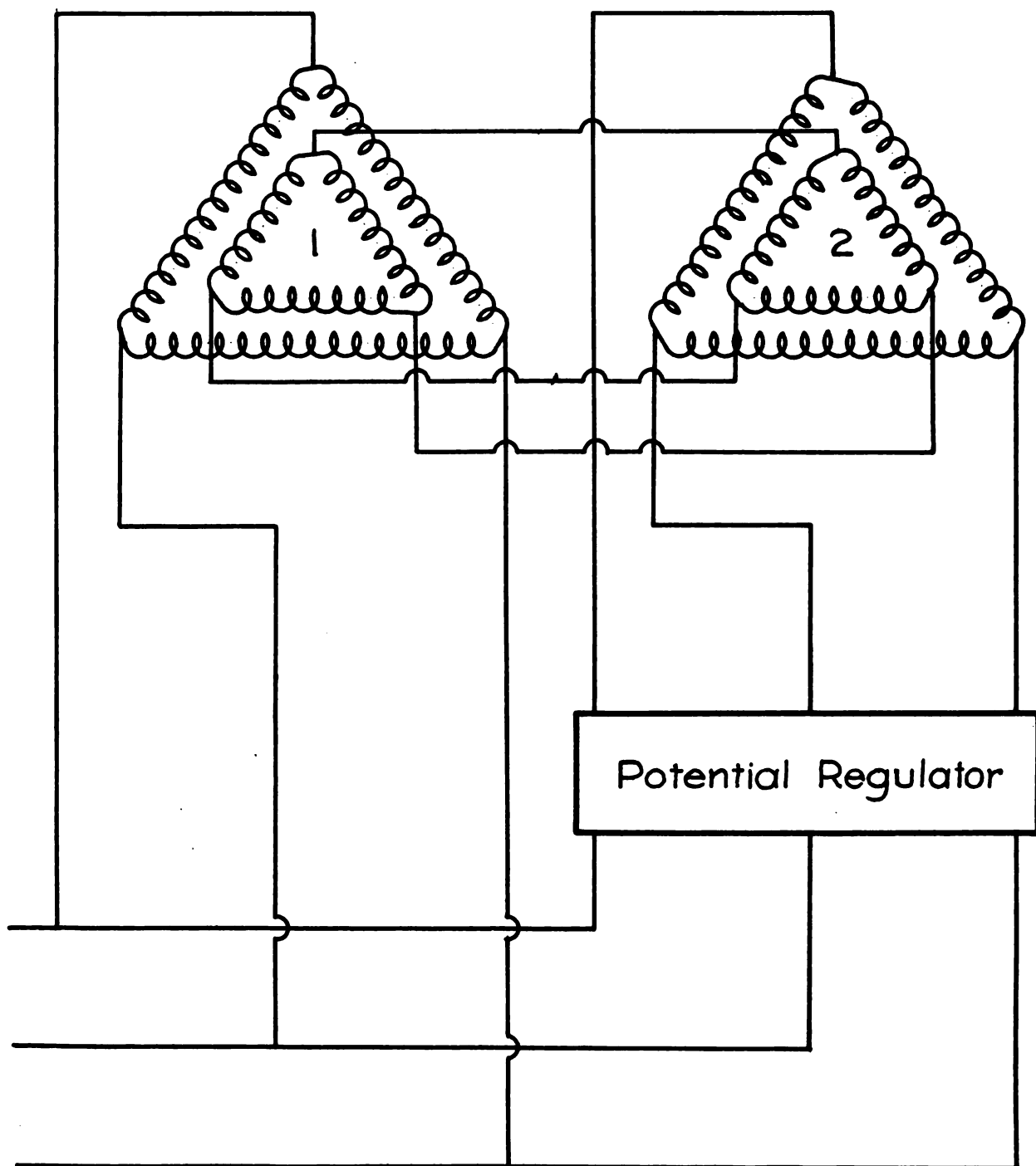


FIG. 4.

pressed on the primaries. From the data obtained a curve was plotted between volts and mechanical degrees. The point where the curve cut the zero axis of voltage represented the required position of the rotors.

The first series of runs were made by varying the position of the rotors from the zero position to 180 electrical degrees shift and varying the voltage impressed on one of the machines by means of the regulator. The voltage on the other was held constant at 110 volts. Each run was made with both impressed voltages and relative positions of the rotors held constant and the load varied from zero to as much as the machines would carry.

At zero degrees shift of the rotors the machines possessed no torque no matter what values of voltages were impressed on the primaries.

The next few runs were made with the rotors connected at 30, 60, 90, 120, and 180 electrical degrees shift and impressing voltages of 88, 110, and 132 volts on the second machine for each shift. The data and results obtained were plotted in the form of curves using torque as abscissae and power factor of each machine, current of each machine, efficiency of set, and speed as ordinates. These curves are shown in figures 5 to 20 inclusive.

It will be seen that at any one of the three voltages corresponding curves are very similar. An increase in the electrical shift for any voltage increases the speed and efficiency for any given load and increases the power factor of

of machine No. 1 which has a constant impressed voltage of 110 volts. The current in this machine decreases with an increase in the shift. The power factor of machine No. 2 rises very rapidly for any one shift but decreases as the shift increases. The current in this machine increases as the shift increases.

At the lower shifts the slip increased more rapidly and the machines would not carry as heavy a load. In fact as the electrical degree shift approached zero the torque approached zero.

In order to obtain a lower voltage than 88 volts, three single phase transformers were used having a ratio 1 to 1. The primary side of these transformers was connected in star and the secondaries in delta. This gave a voltage on the secondary side of $\frac{110}{\sqrt{3}} = 63.5$ volts. By means of the regulator this was reduced to 48 volts. The above runs were then repeated using different shifts.

The curves for these runs are shown in figures 21 to 25 inclusive. It will be seen that there is very little change in the shapes of the curves as compared with the other runs and that the values on corresponding curves for a given value of the torque are only slightly different.

Using a constant torque of 8 foot-pounds, points were taken from the various speed curves and plotted against voltage as shown in figure 26.

It will be seen that the average trend of the curves is to increase as the voltage increases. The drop in the curves at the point of equally impressed voltages on both machines

is apparently due to the fact that no regulator was used. Curve "A" was taken with the regulator in and the speed under these conditions is a maximum at equally impressed voltages. The regulator evidently caused a phase shift of the voltages and the currents in the second machine in such a way as to change the electrical shift of the rotors. The regulator has, therefore, introduced this error in all the runs in which it was used. Voltage measurements were taken on the regulator to determine this error and it was found to be about 14 degrees.

From the power factor curves already plotted points were taken at a constant torque of 16 foot-pounds and plotted against voltage as abscissae. These curves are shown in figures 27 and 28.

It will be seen that as the voltage is increased on machine No. 2 the power factor of machine No. 1 falls off. The power factor of machine No. 2 at shifts of 60 and 90 electrical degrees rises to a maximum value and then falls off. This maximum point seems to be about the same whatever the shift but the greater the shift the lower the voltage that is required to make the power factor a maximum.

In all of the runs so far described the secondary current for any given load increased as the electrical degree shift decreased. At shifts of 30 and 60 degrees it rose to abnormal values on loads considerably under the rated load of the machine.

The effect was next tried of disconnecting the rotors and several peculiar results were noticed. With the rotors placed in phase opposition the machines would not start with

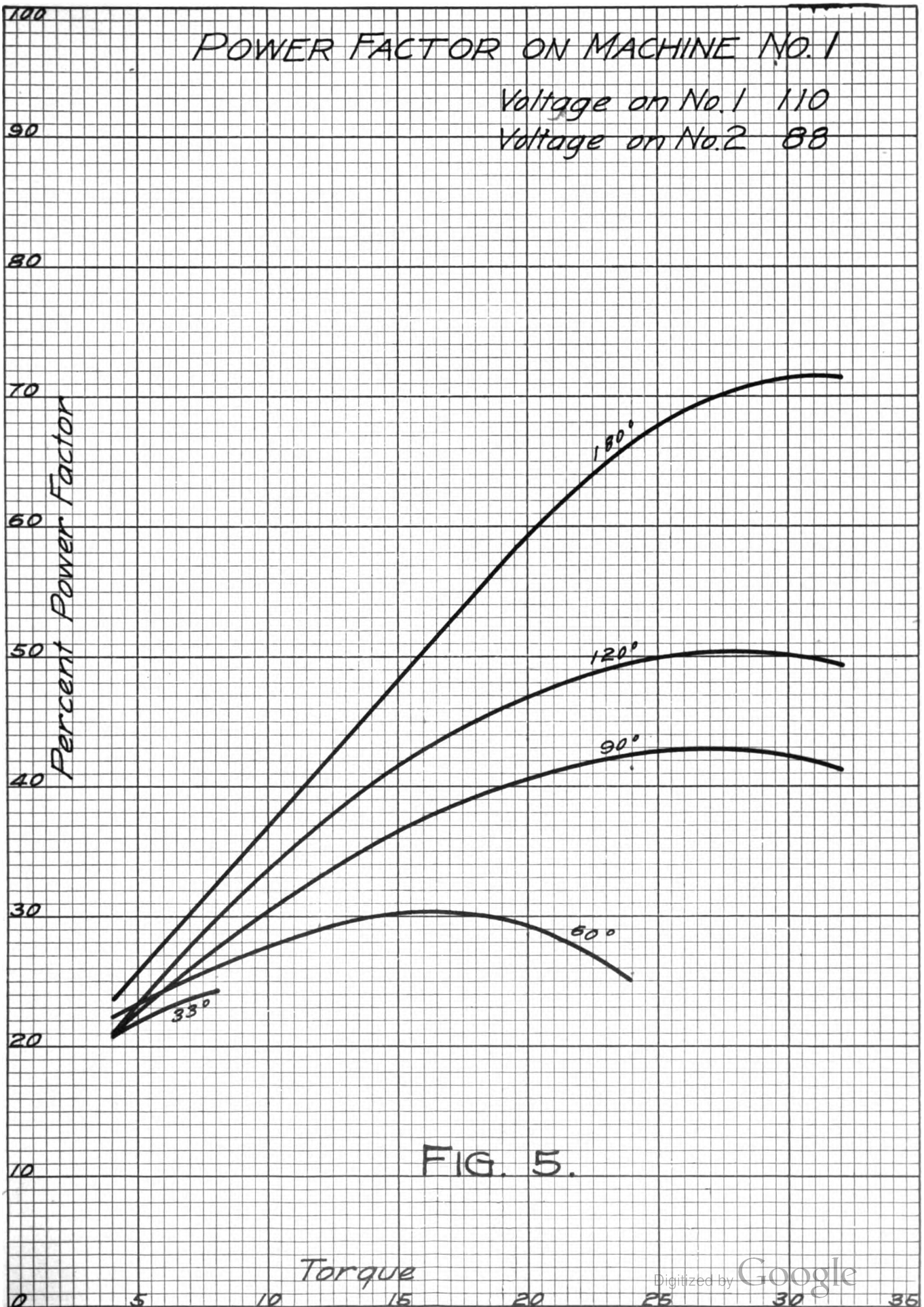
110 volts impressed on machine No. 1 and any voltage from 88 to 132 impressed on No. 2. In this phase position the rotors were also locked electrically with respect to each other. If the rotors were shifted 10 degrees from phase opposition and then the current turned on they were immediately pulled into phase opposition. If the rotors were shifted about 20 mechanical degrees off and the voltage on machine No. 2 made 110 volts or less the machines would start and continue to run in perfect synchronism but with little torque. If the machines were started with 130 volts on No. 2, machine No. 1 would run at exact synchronous speed and No. 2 would have a small slip depending on the load. The torque was good. No explanation could be found for the machines acting in synchronism and with no torque in one case and out of synchronism and with good torque in the other.

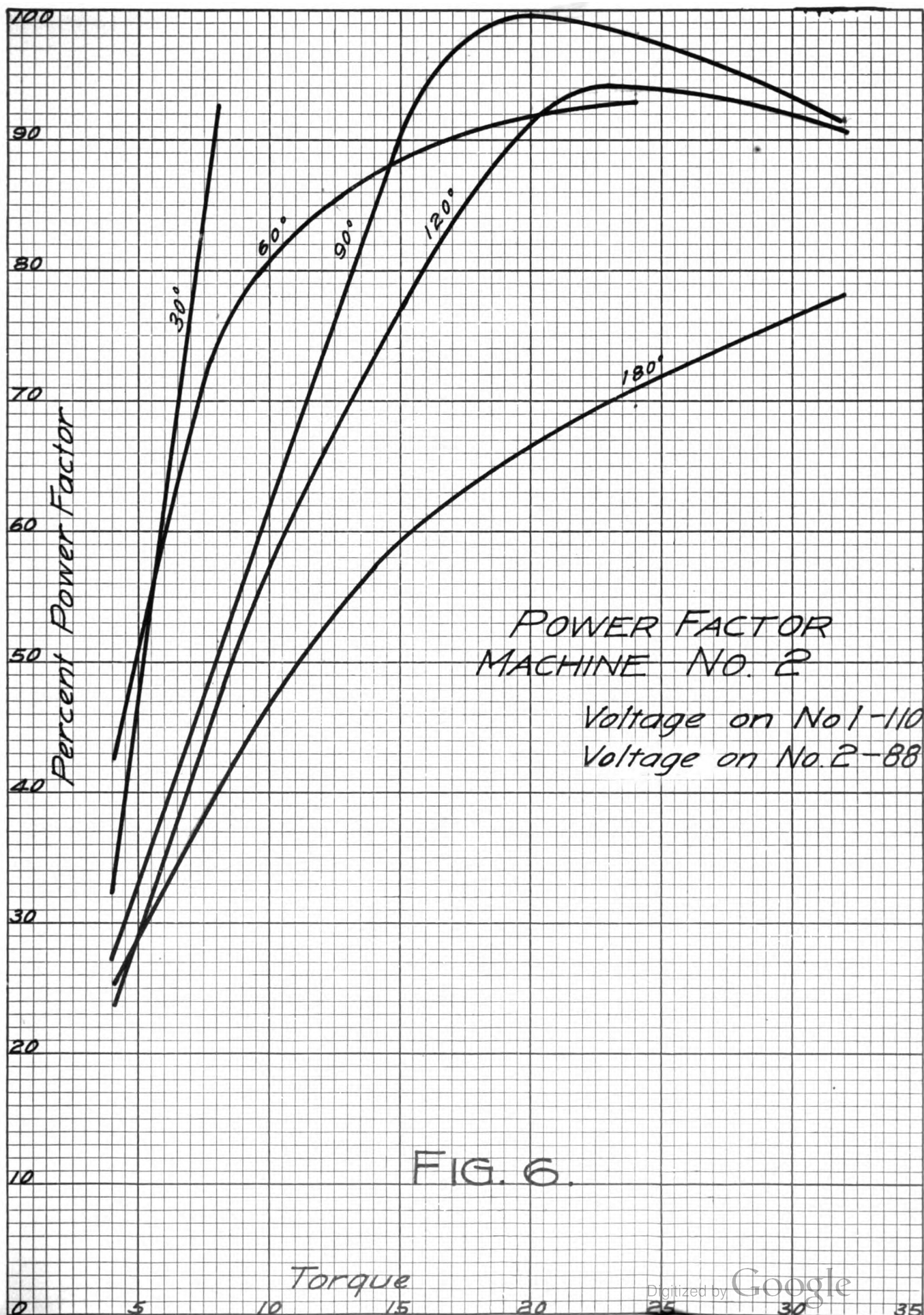
If two secondary phases were interchanged either rotor would run at full speed and the other would remain stationary.

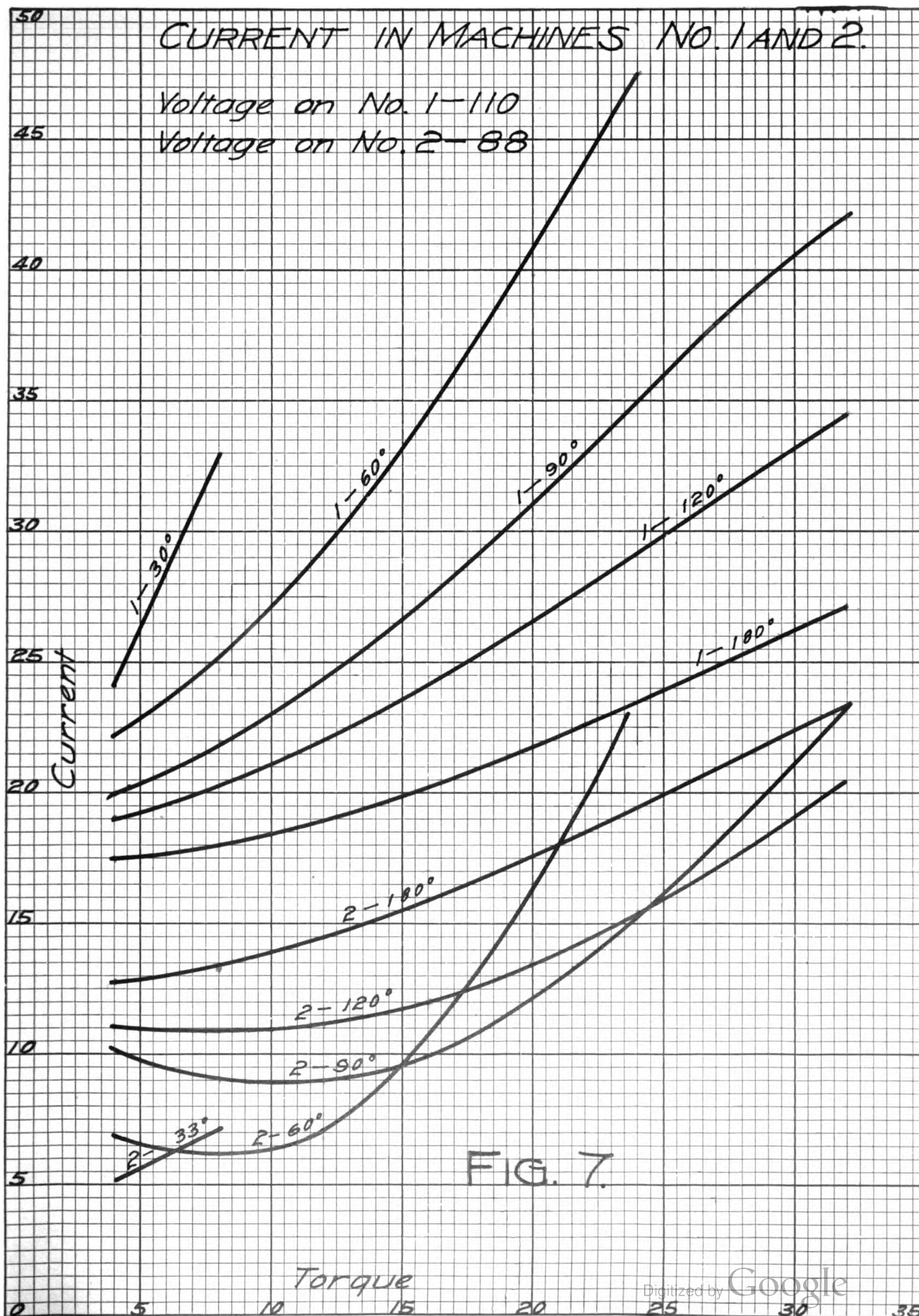
It was also noted that if the rotors were stationary and set for phase opposition with the current on they would shift about 5 mechanical degrees when the regulator was turned from minimum voltage to maximum voltage. This equals 15 electrical degrees and was a proof of our former calculations regarding the phase shift caused by the regulator.

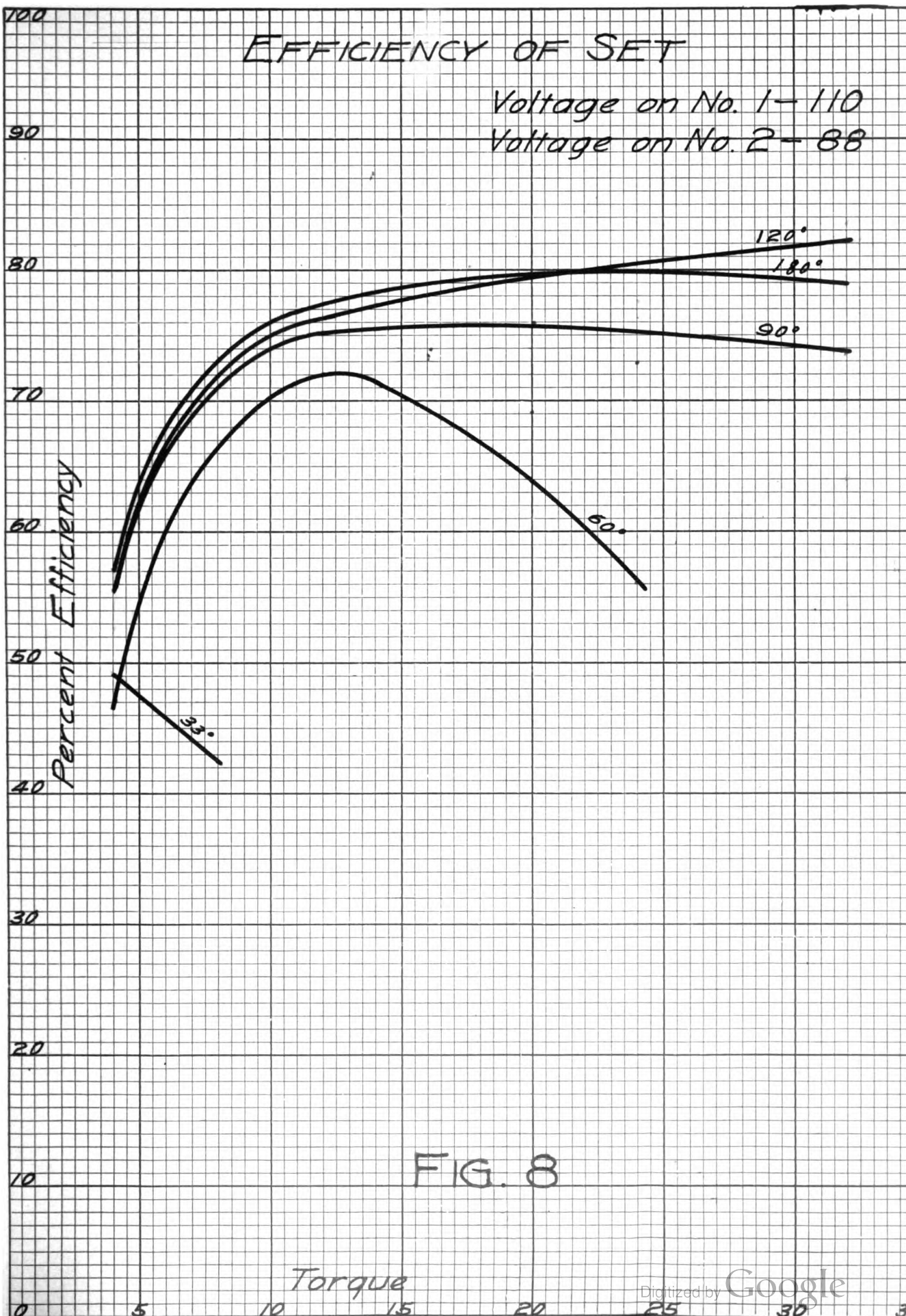
The results obtained from the series of experiments are somewhat indefinite and it is difficult to draw conclusions regarding the behavior of the machine. Unquestionably there is more room for study and experiment in order to gain an insight into the peculiar actions observed. The final results may have no practical value but would nevertheless be interesting.

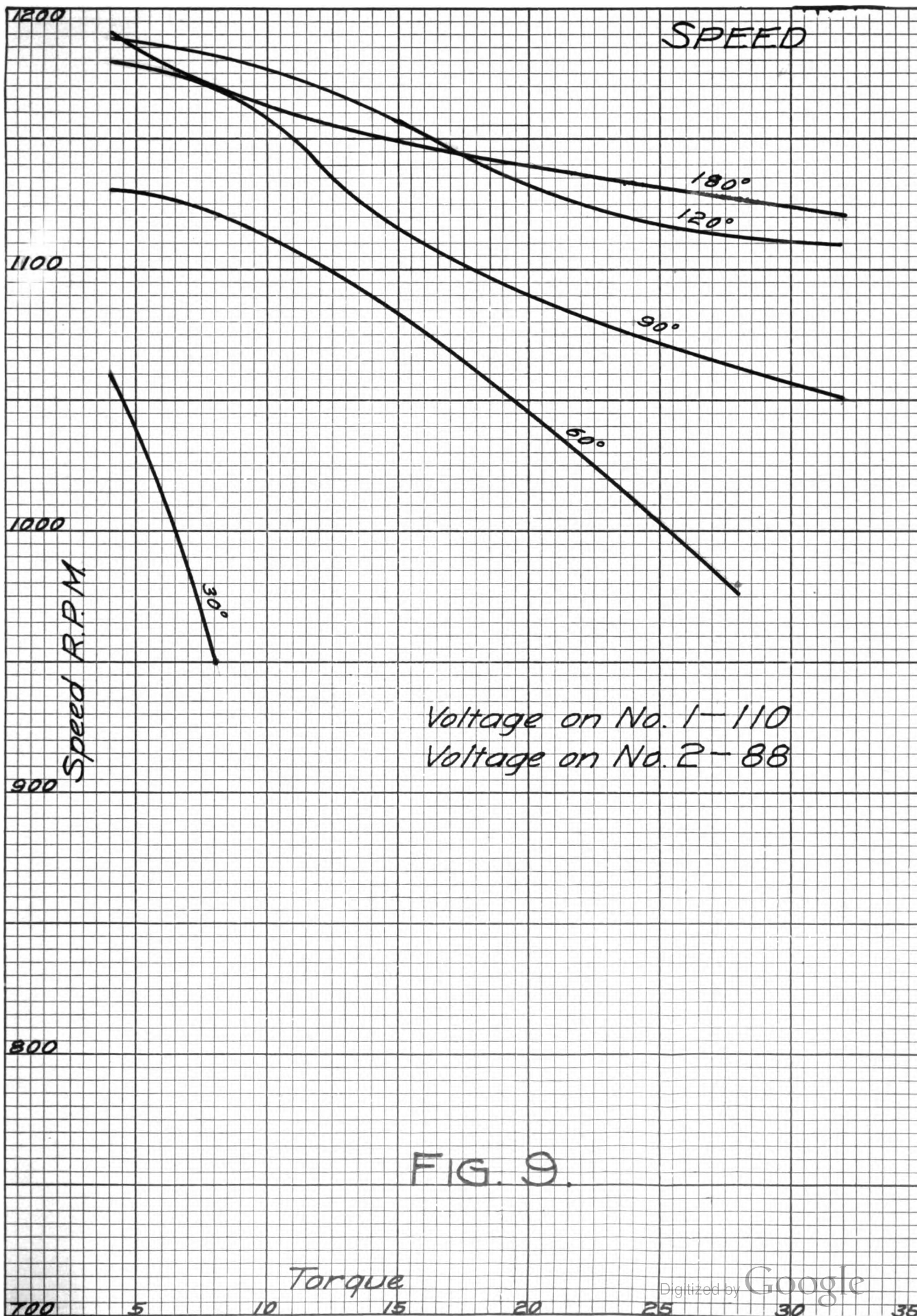
Some suggestions may prove helpful to anyone wishing to make a further study of the subject. A study of the wave form in both primary and secondary circuits might cast some light on the low power factor obtained. Lower voltages should also be tried on one of the machines, being sure in each case of the exact relative position of the rotors to secure phase opposition. Insertion of some resistance in the secondary circuit might help to improve the power factor.











POWER FACTOR OF MACHINE NO. 1. Equally Impressed Voltages

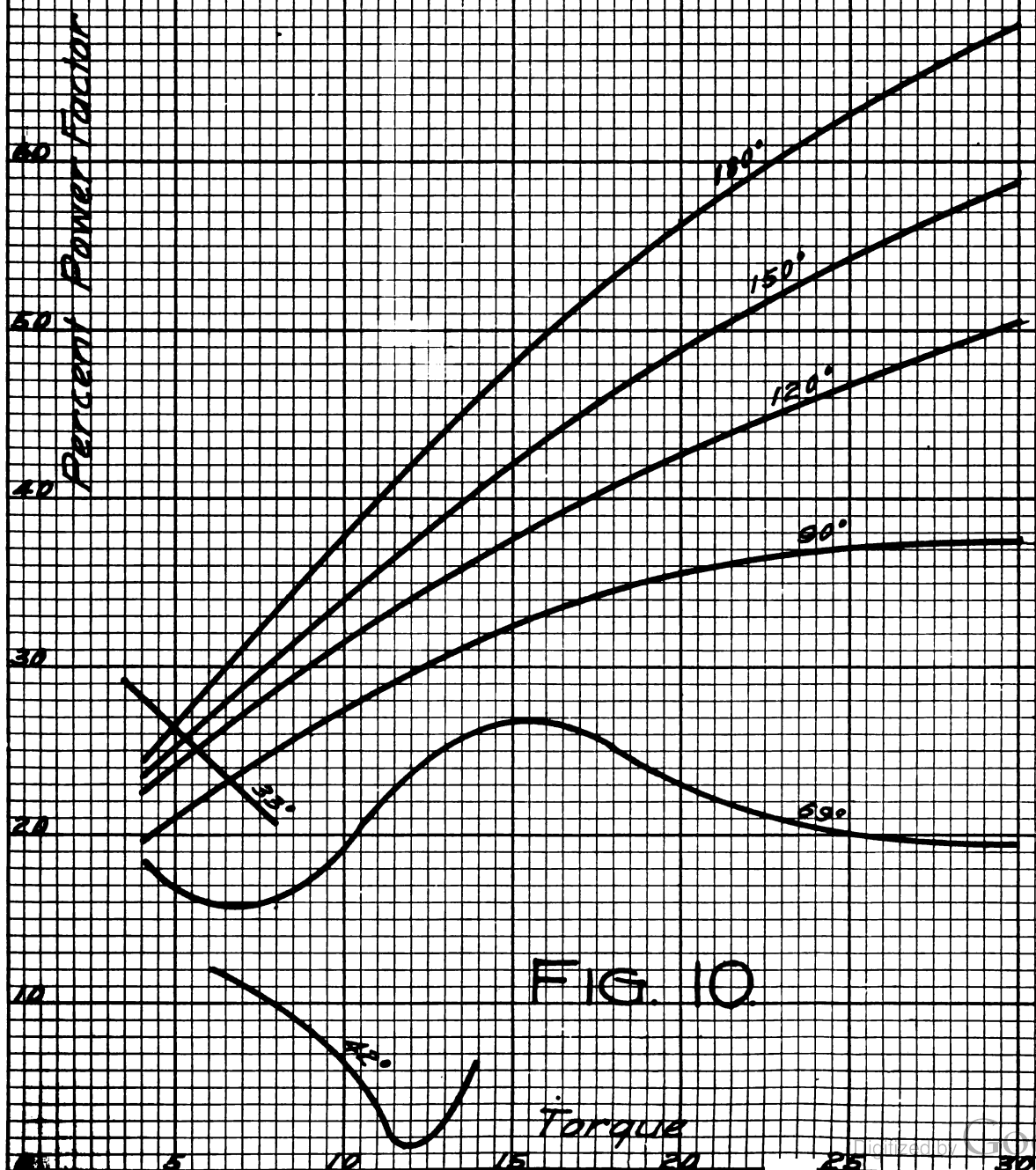
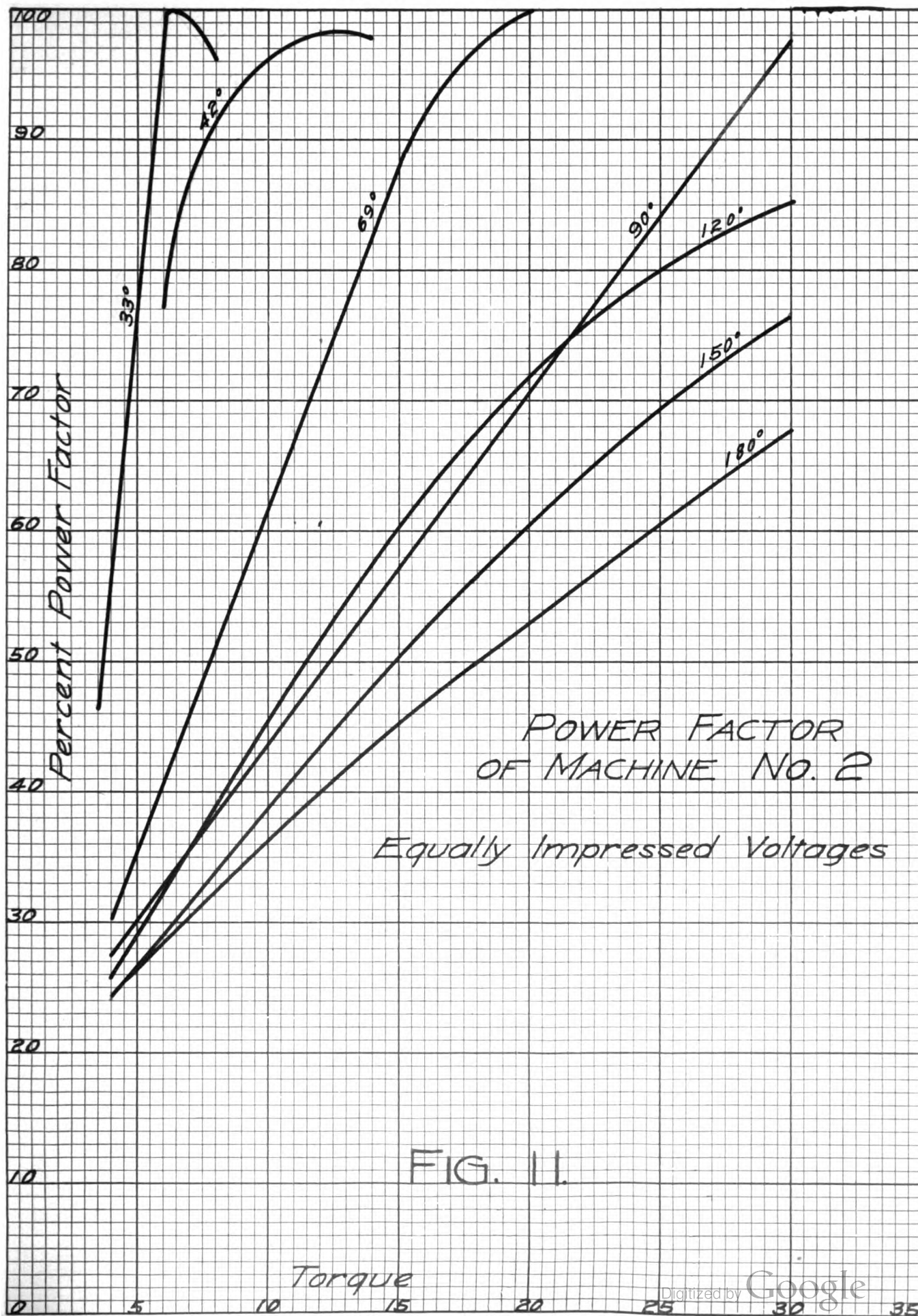
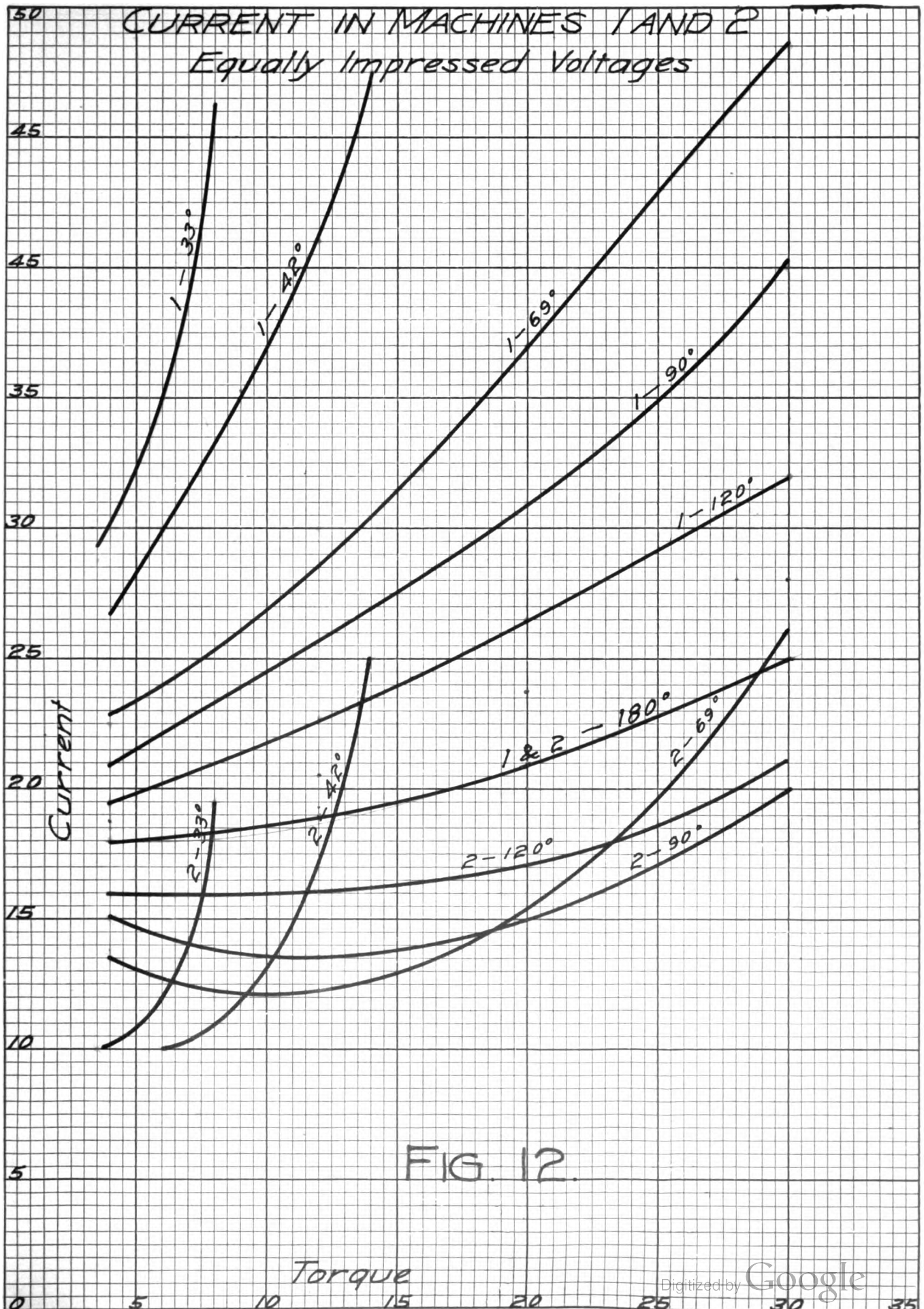
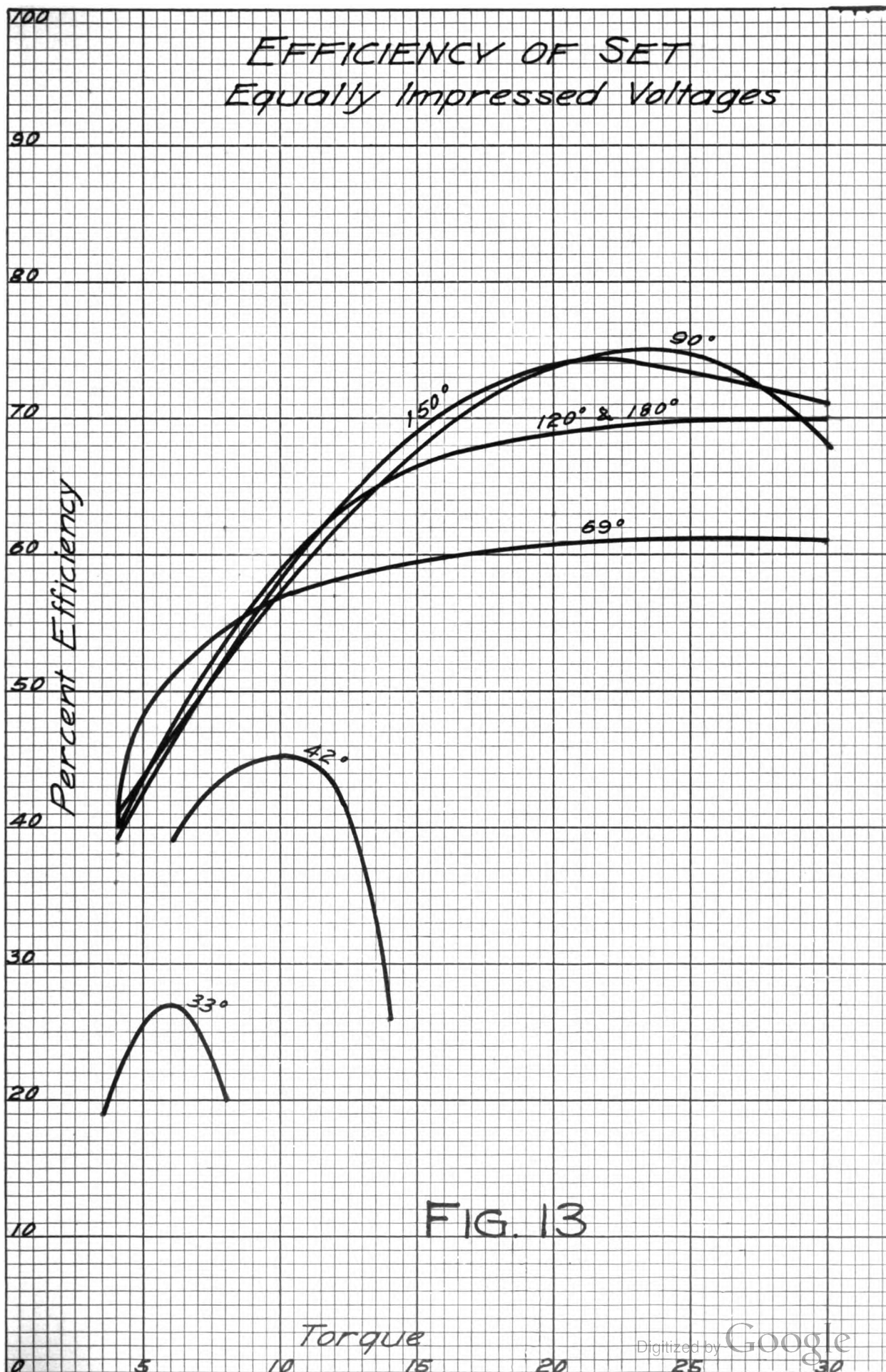
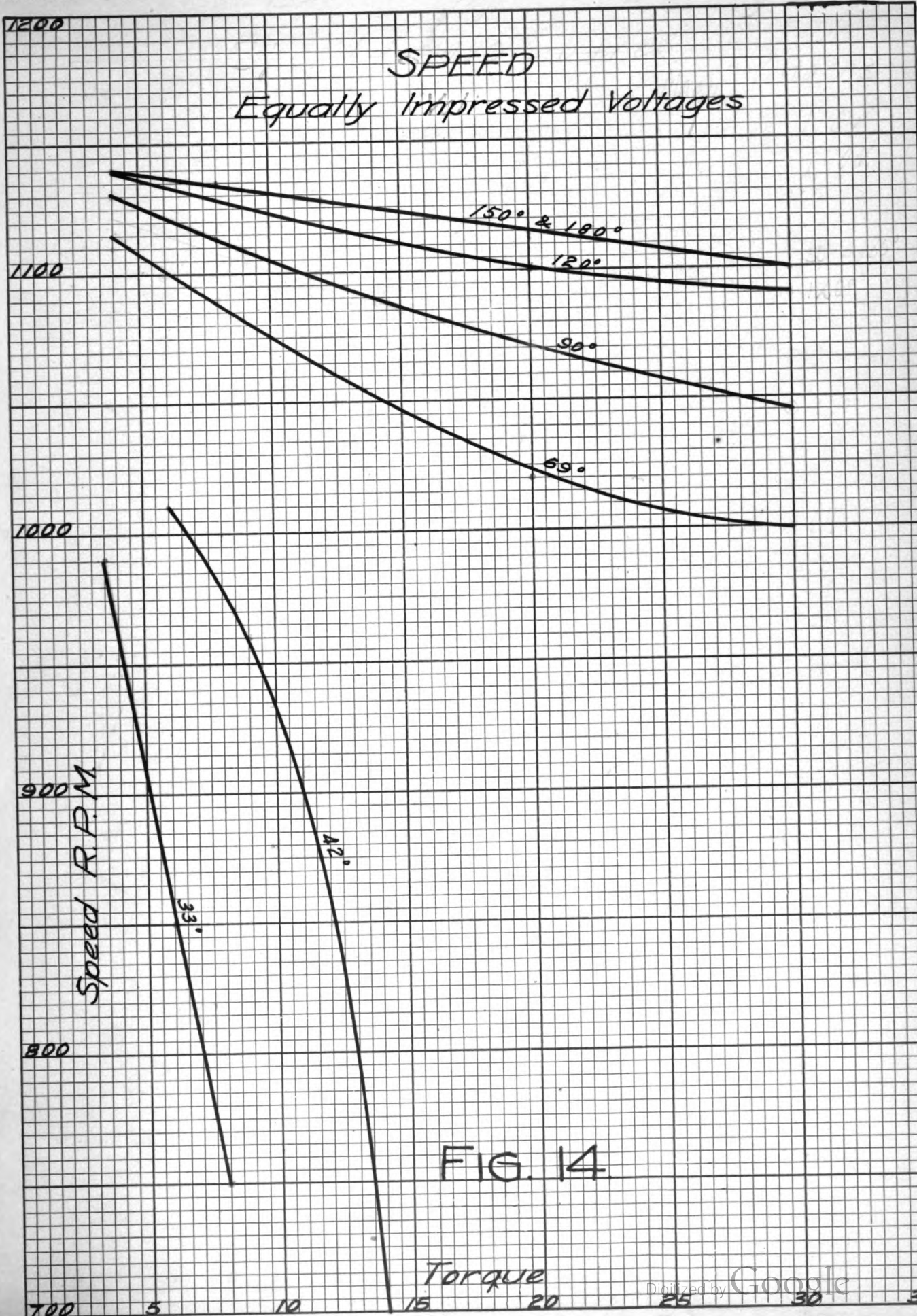


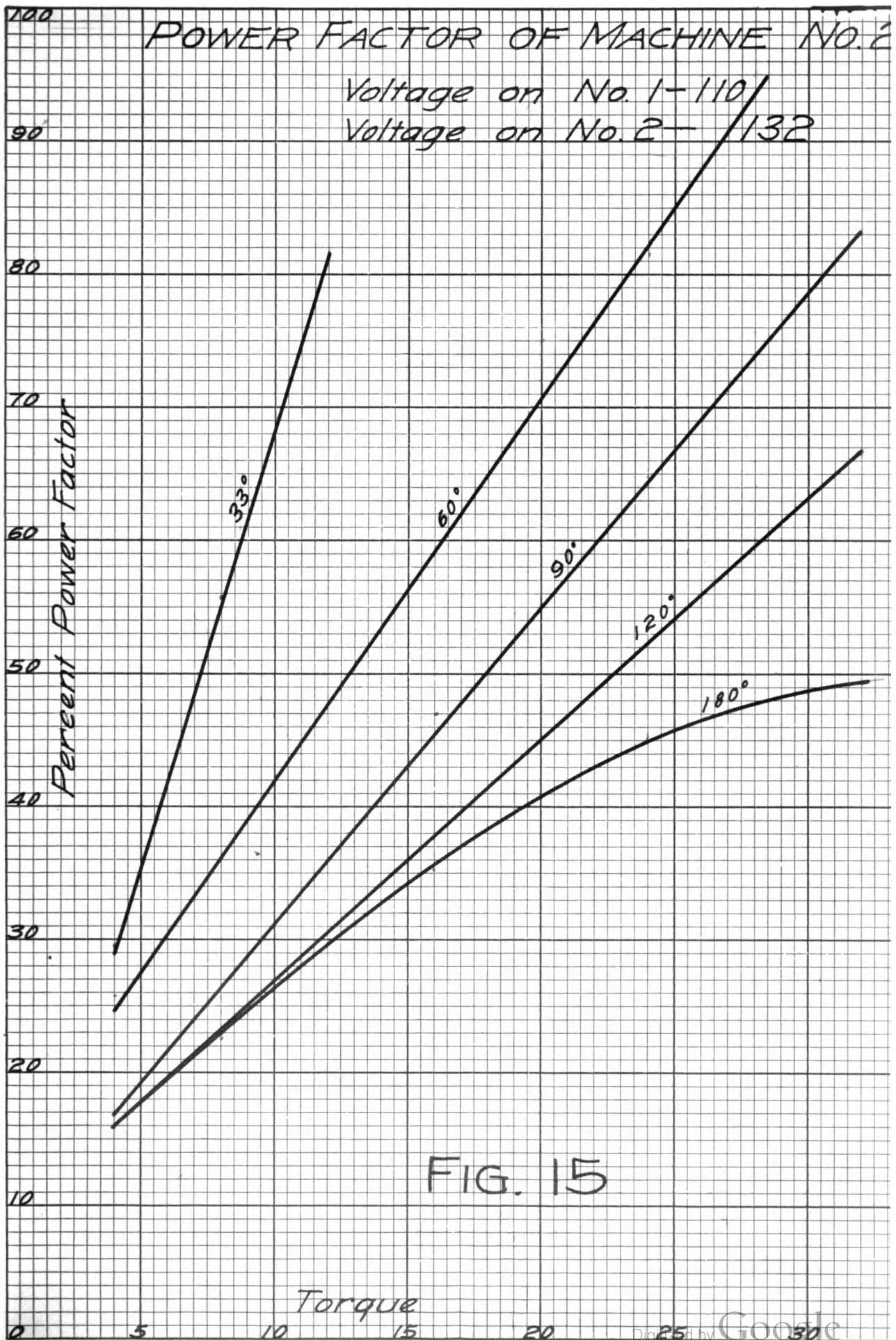
FIG. 10.

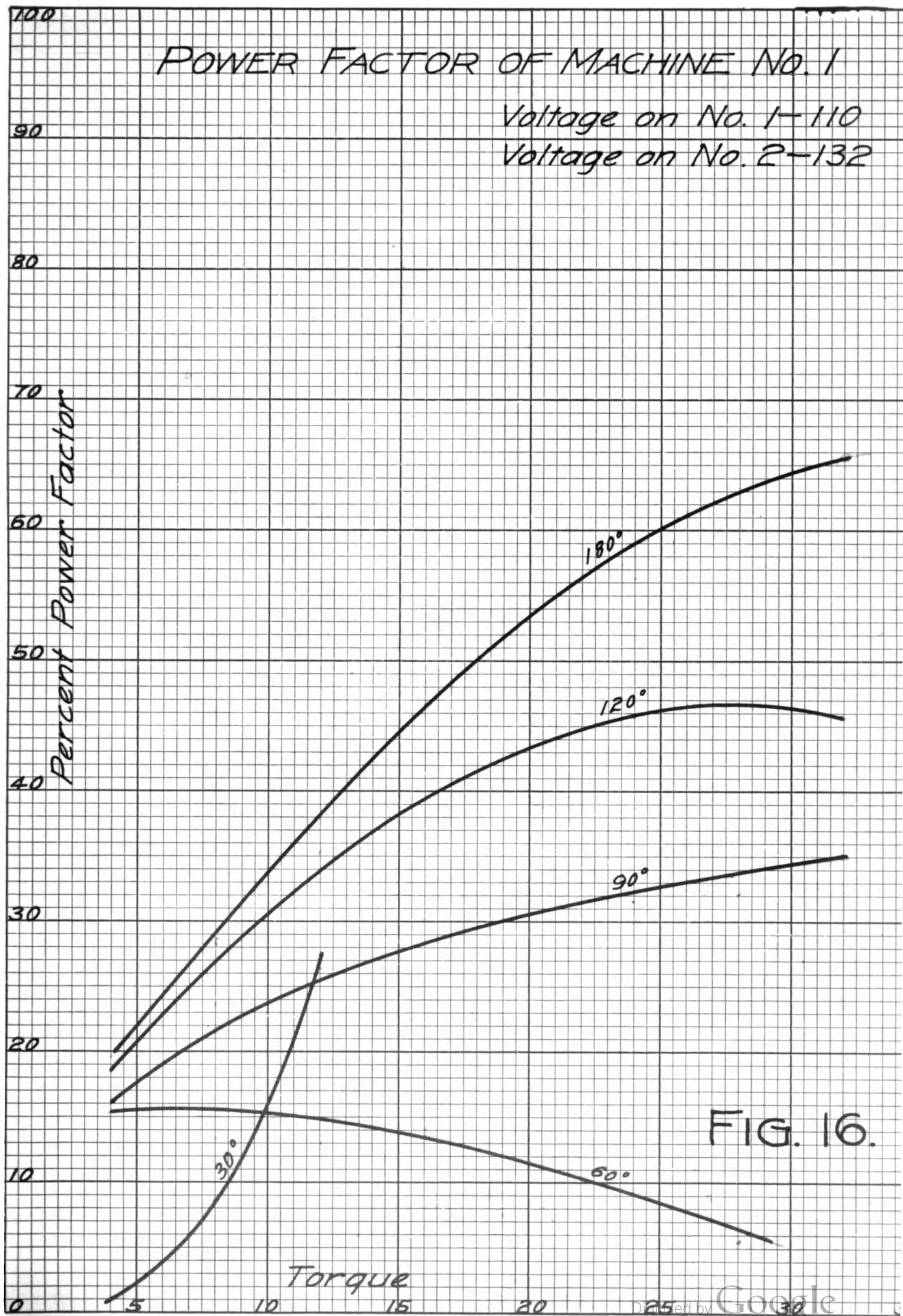


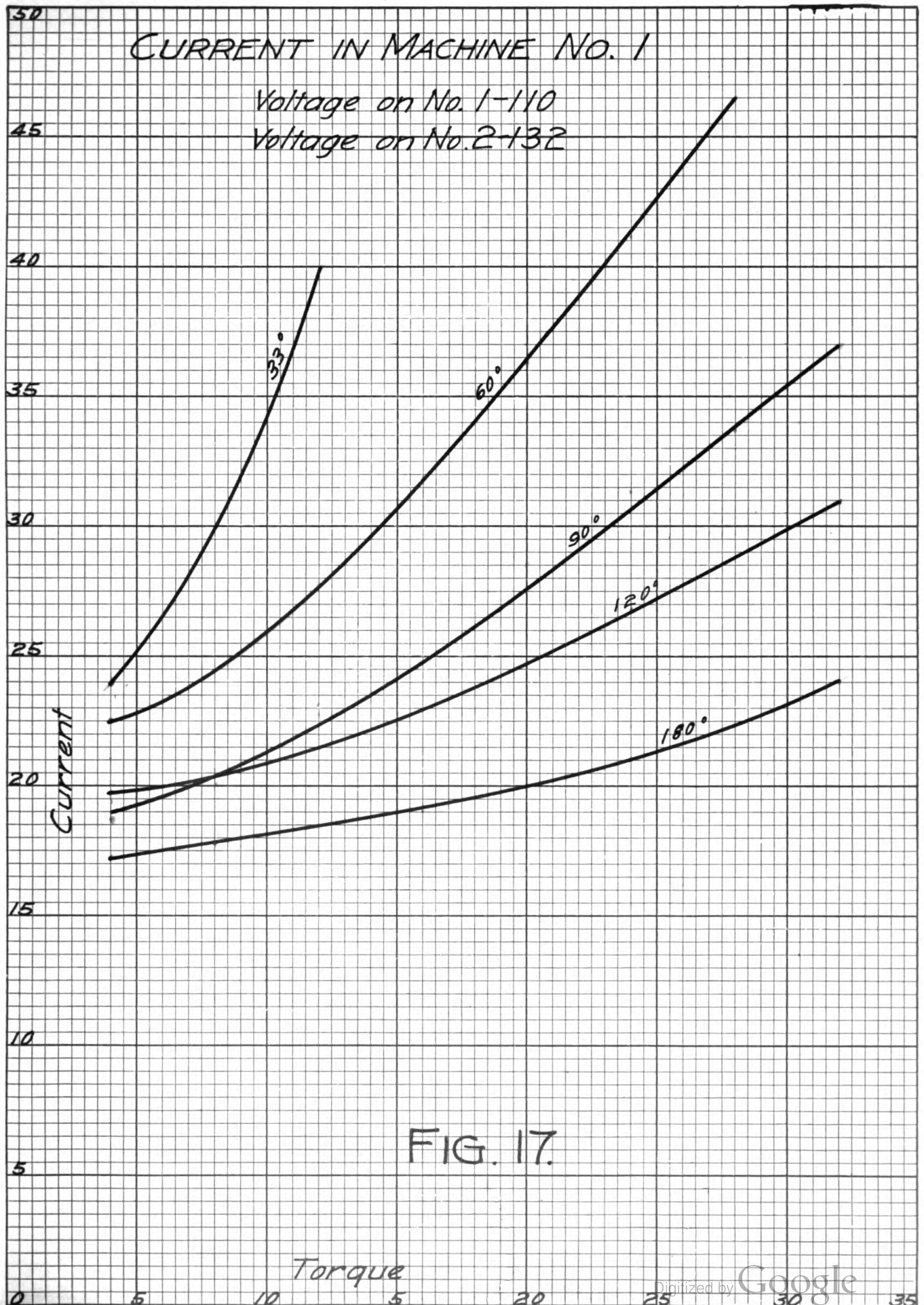


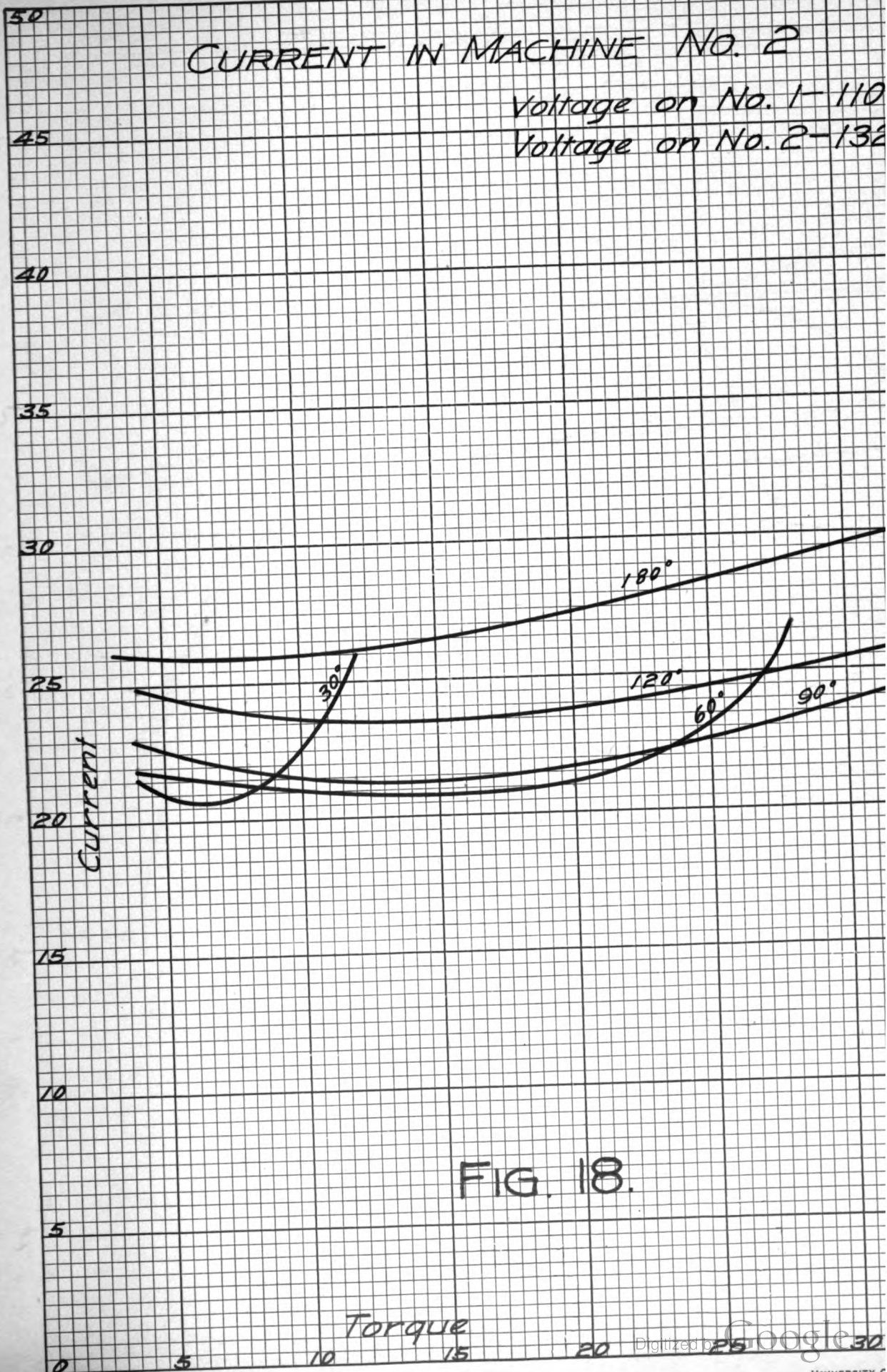


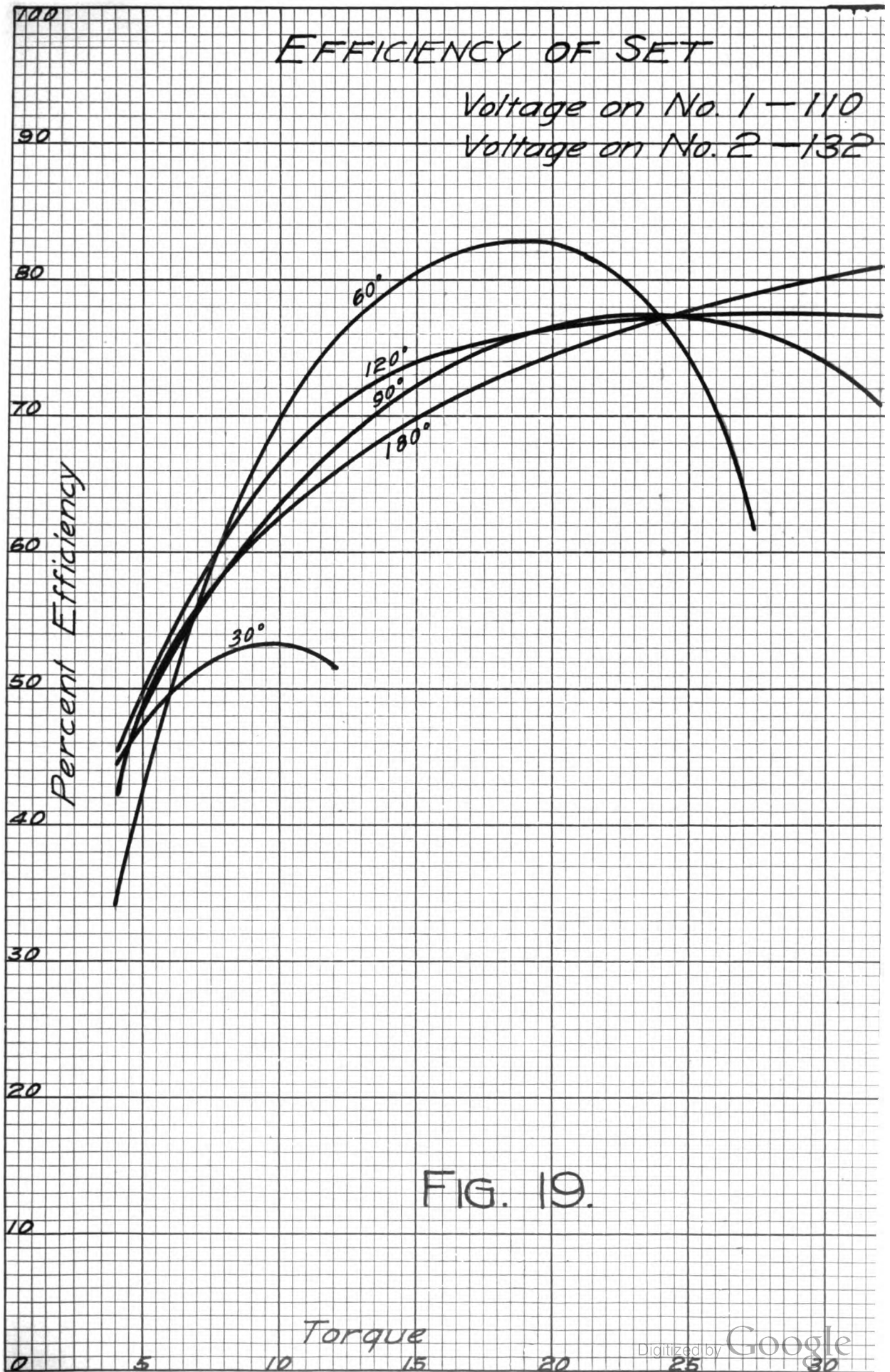












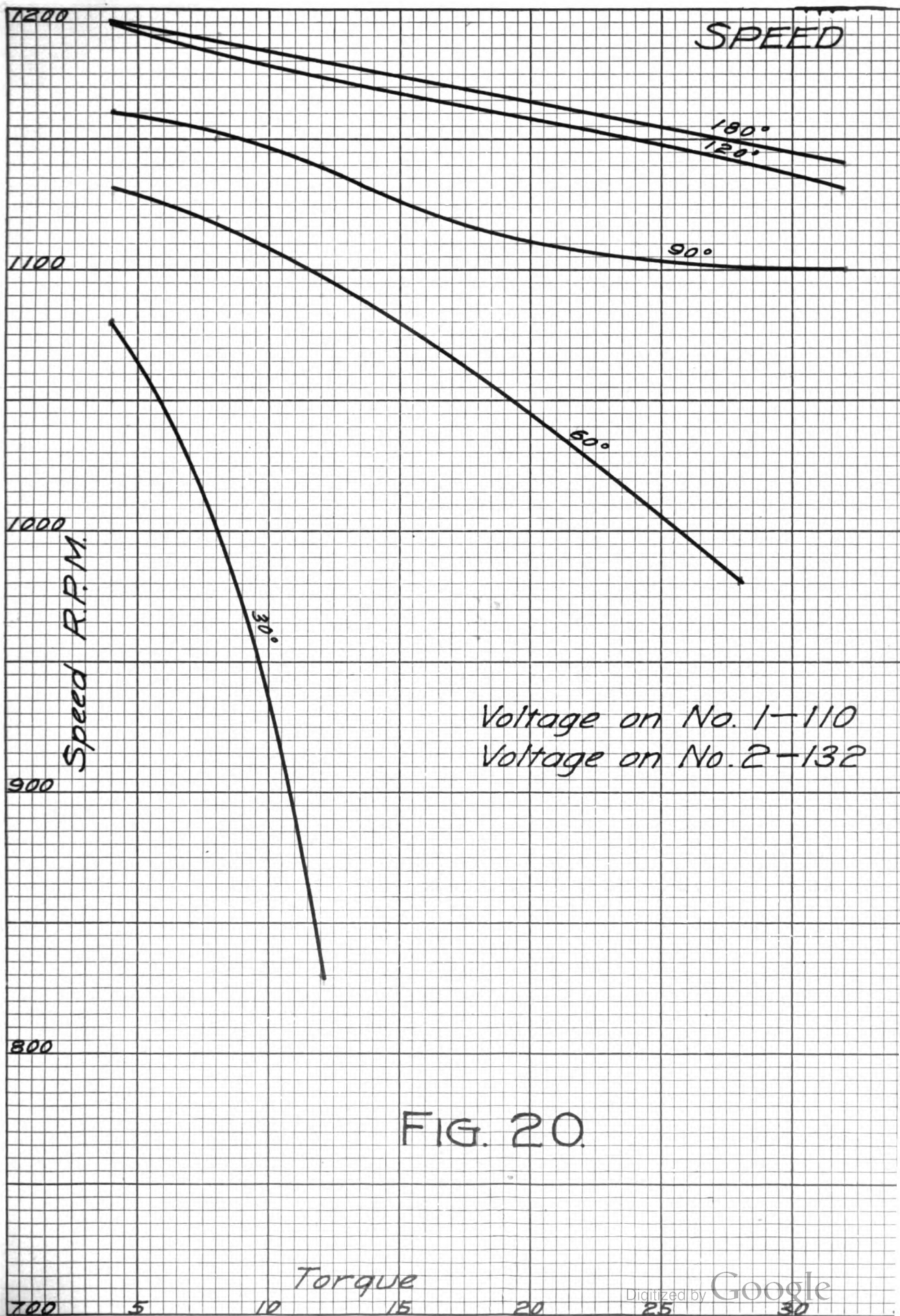
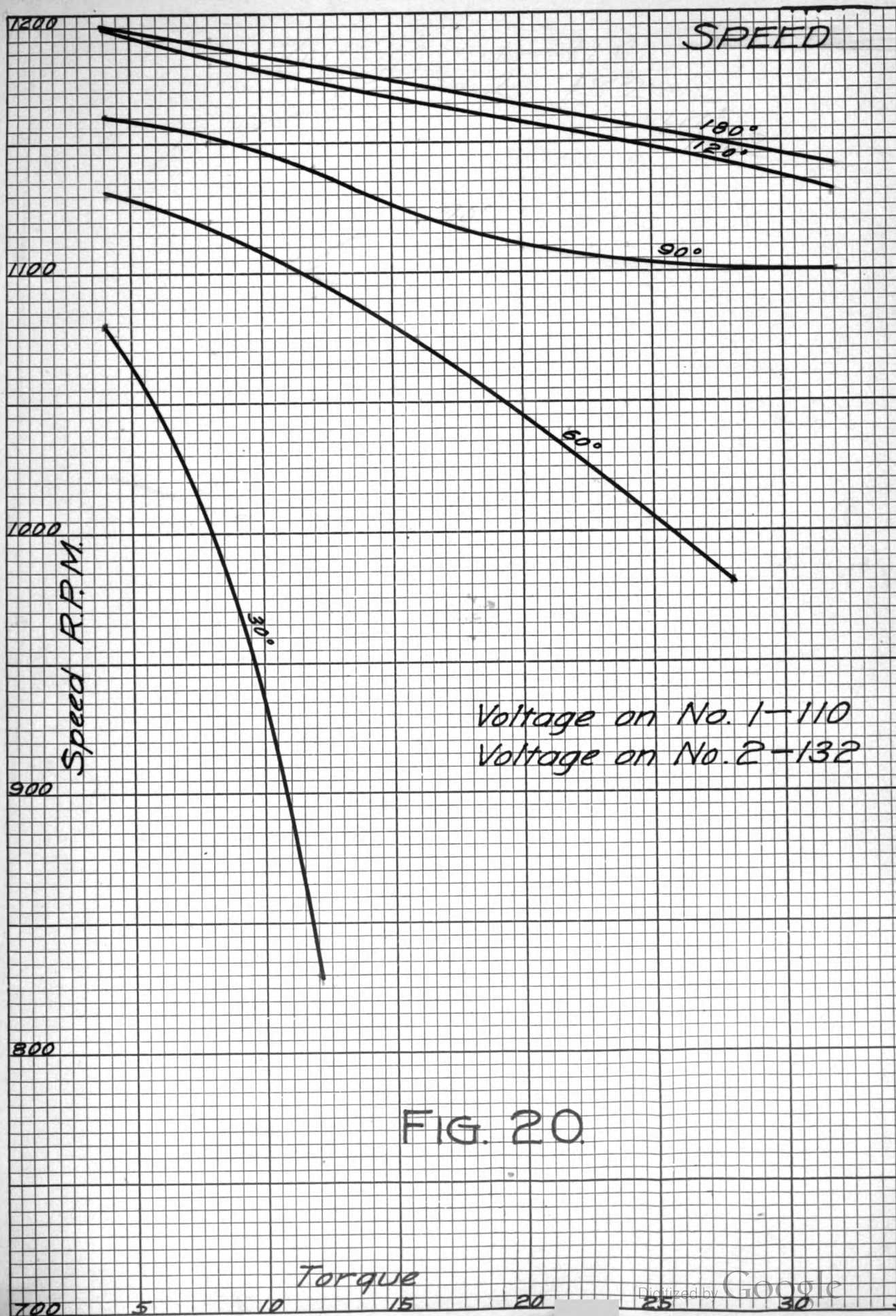
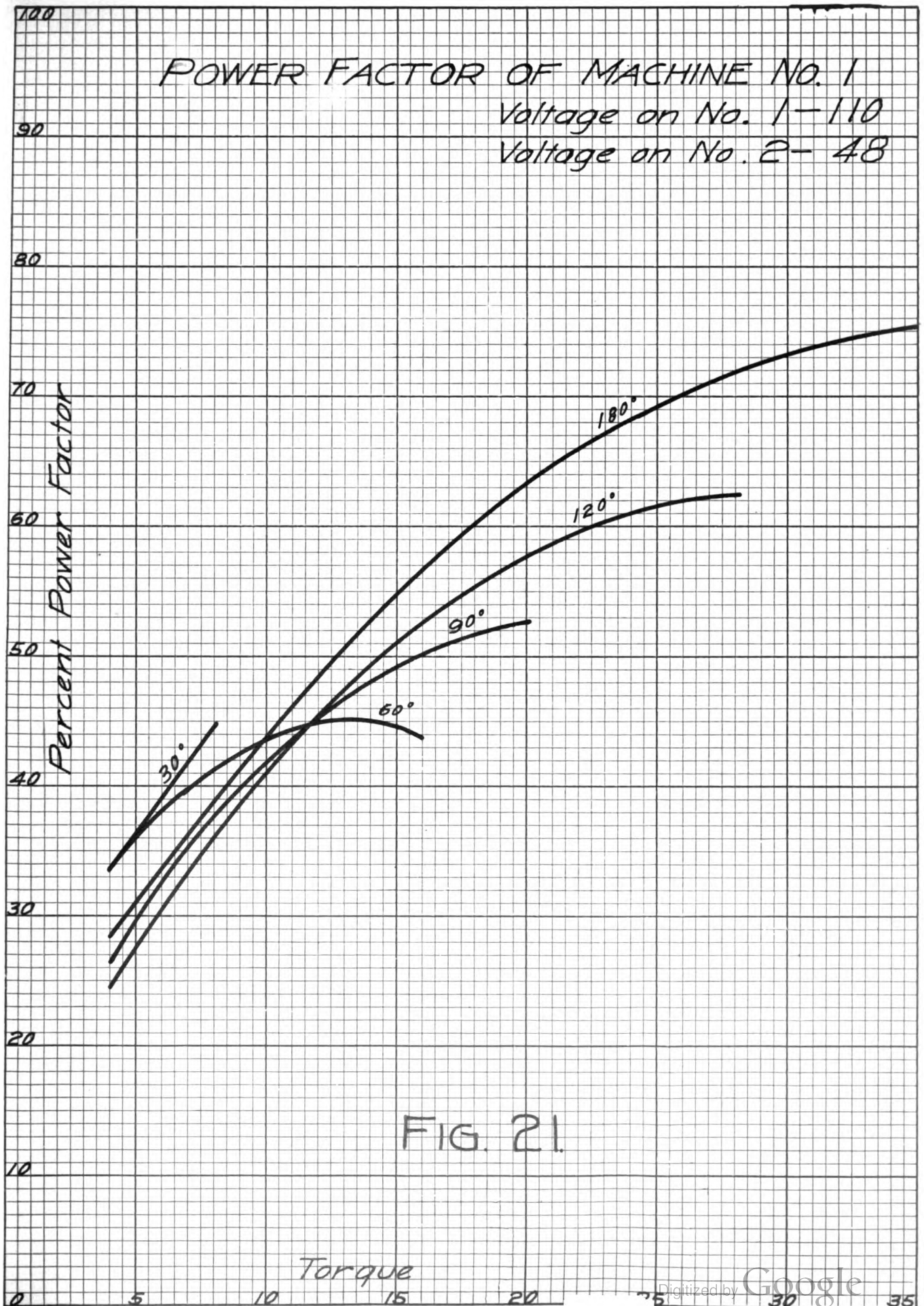
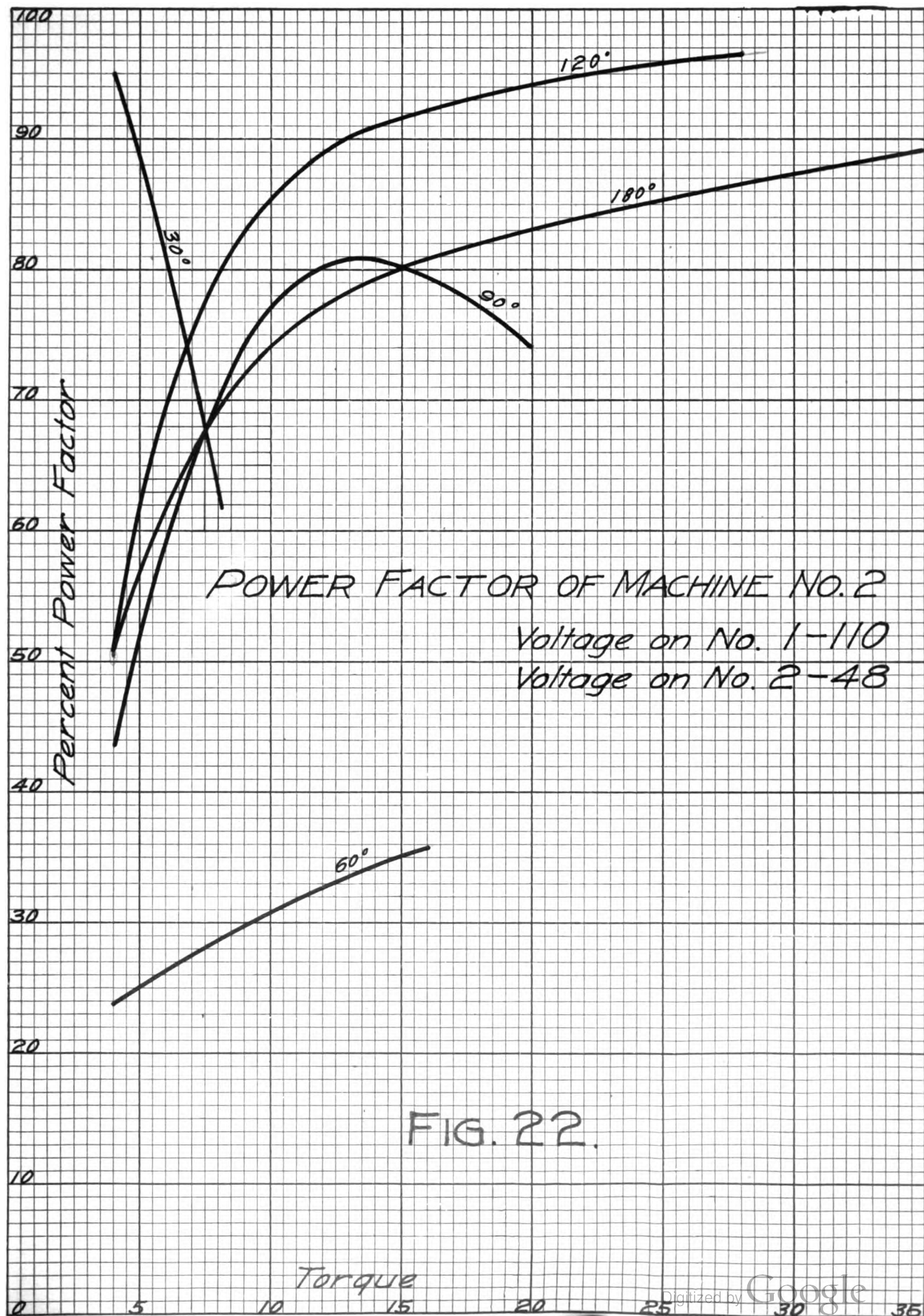
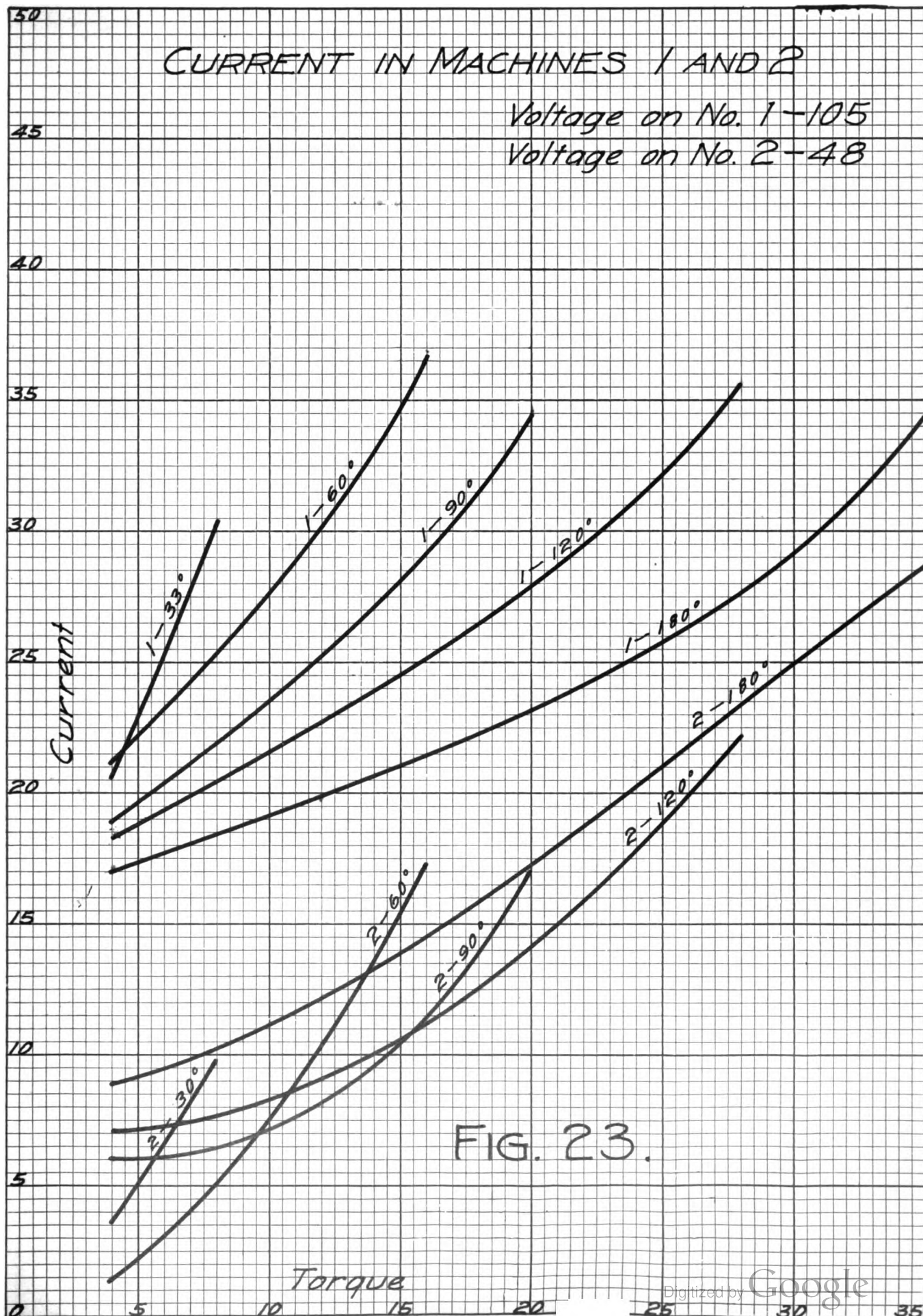


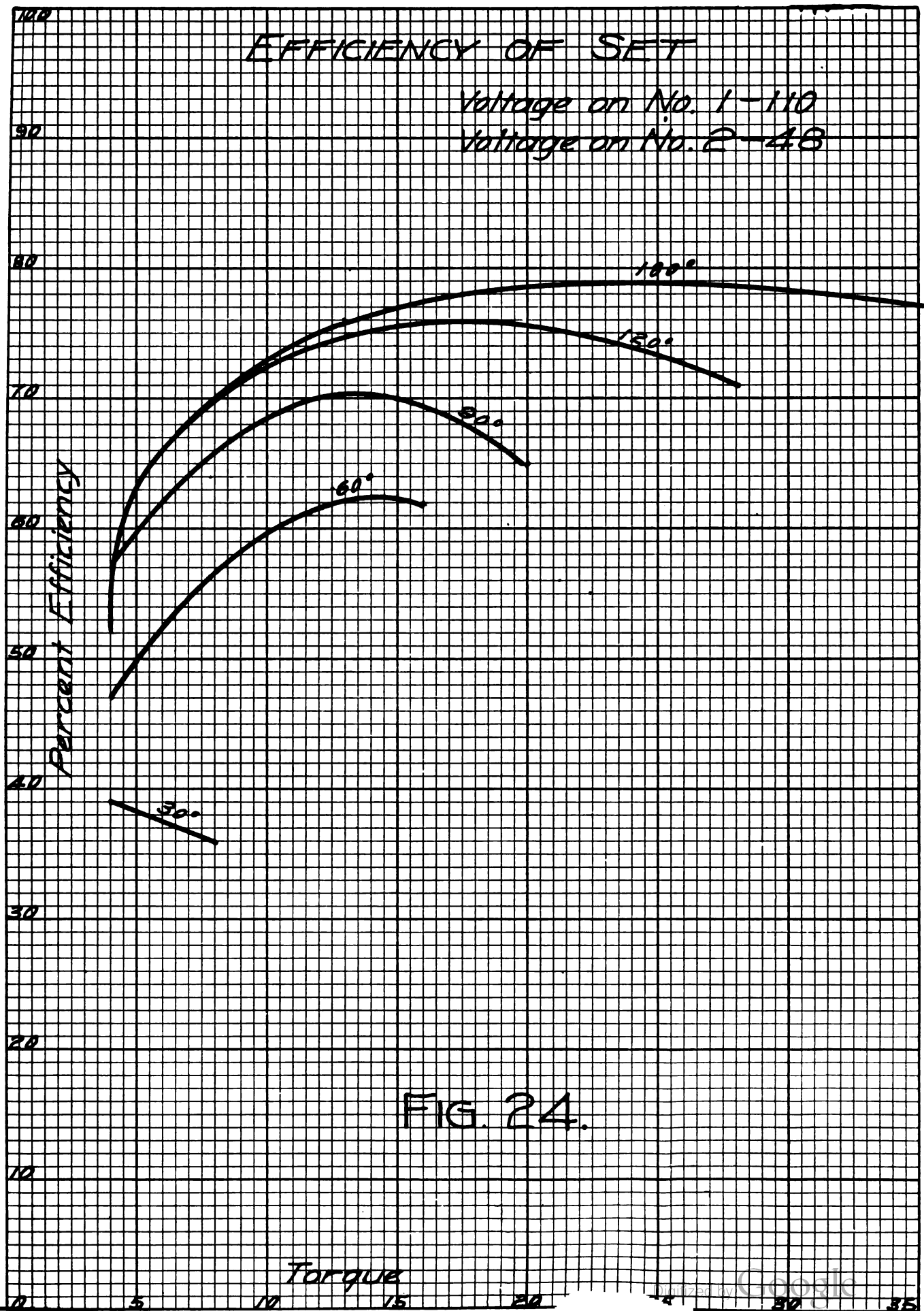
FIG. 20.

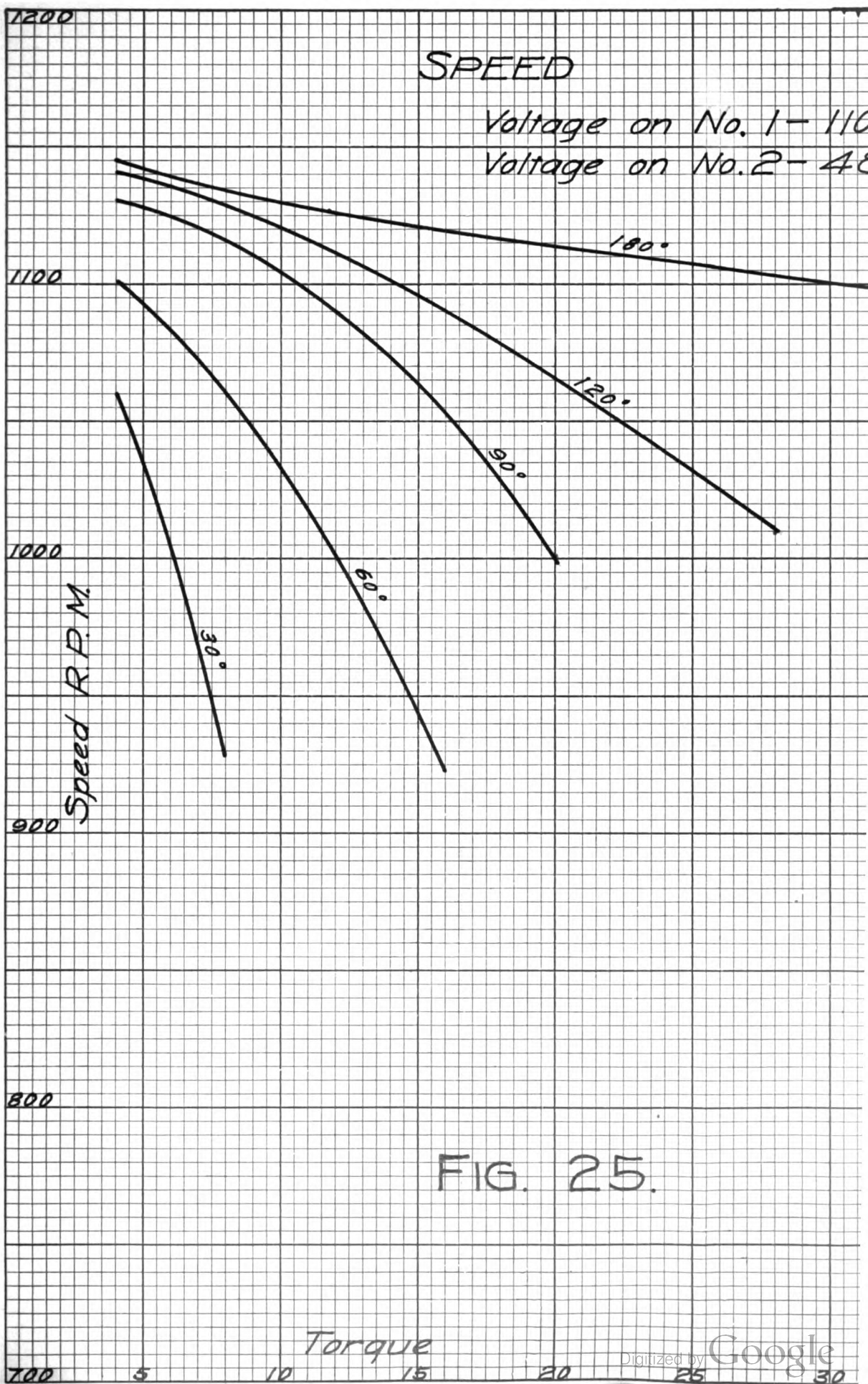


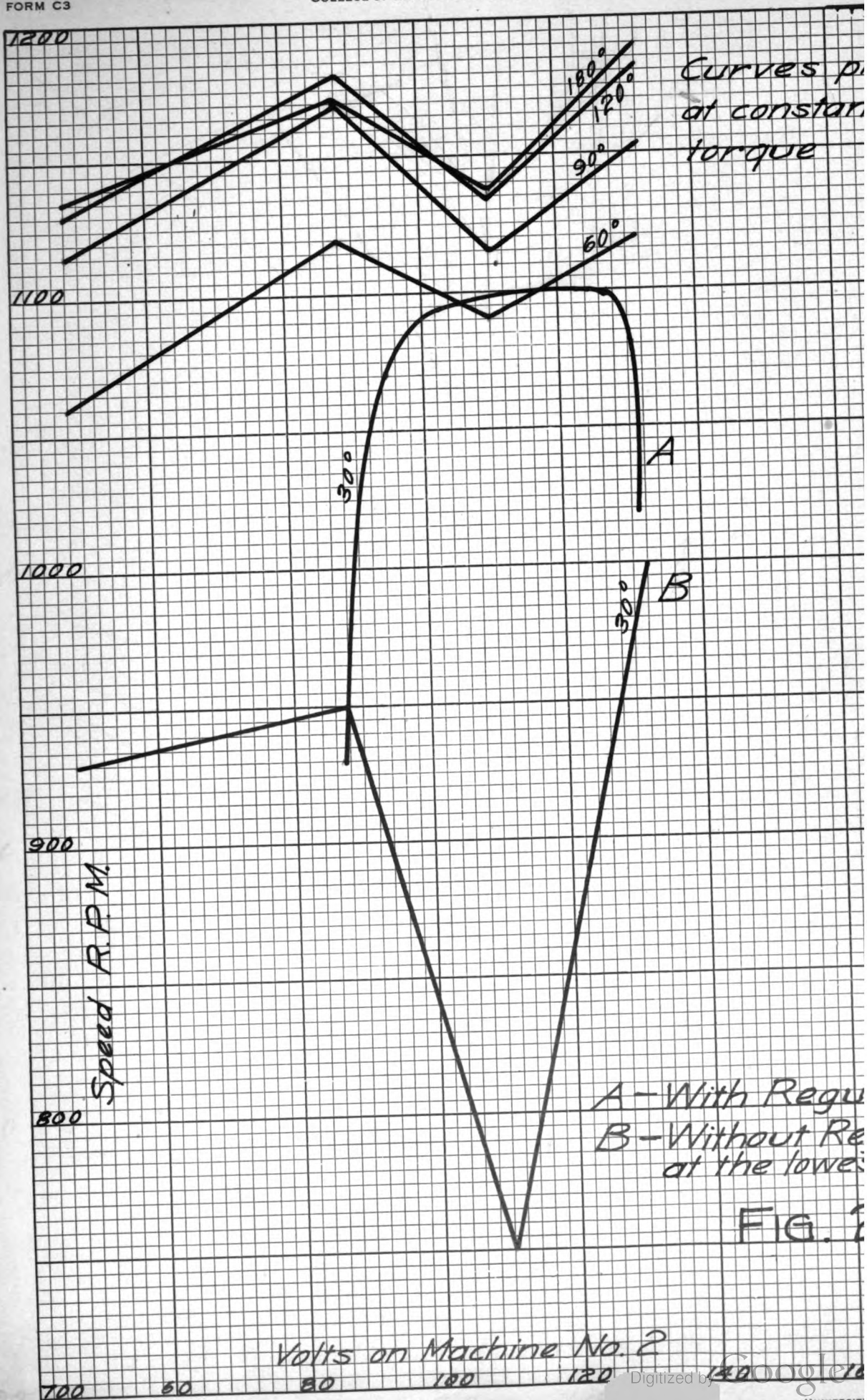


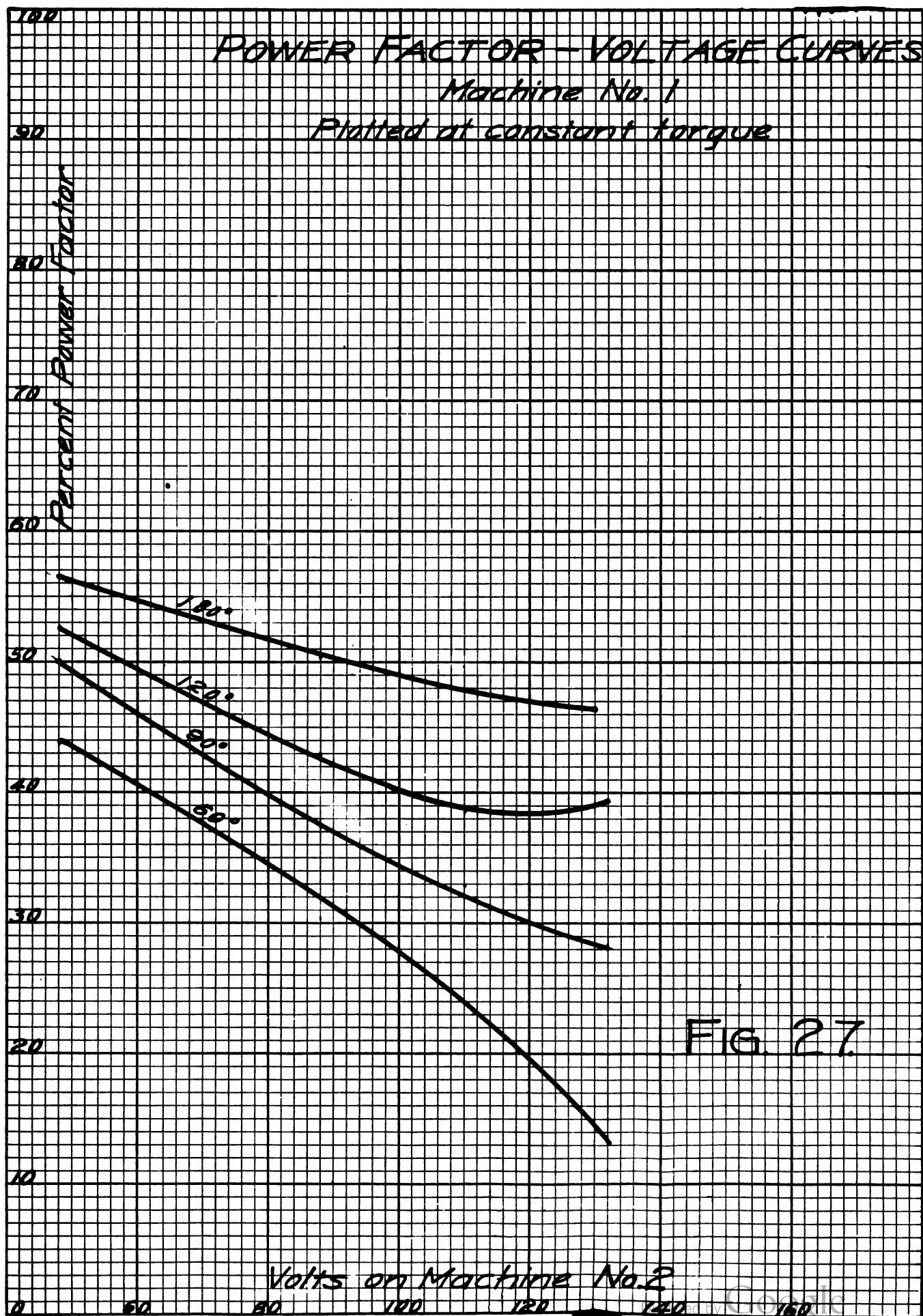


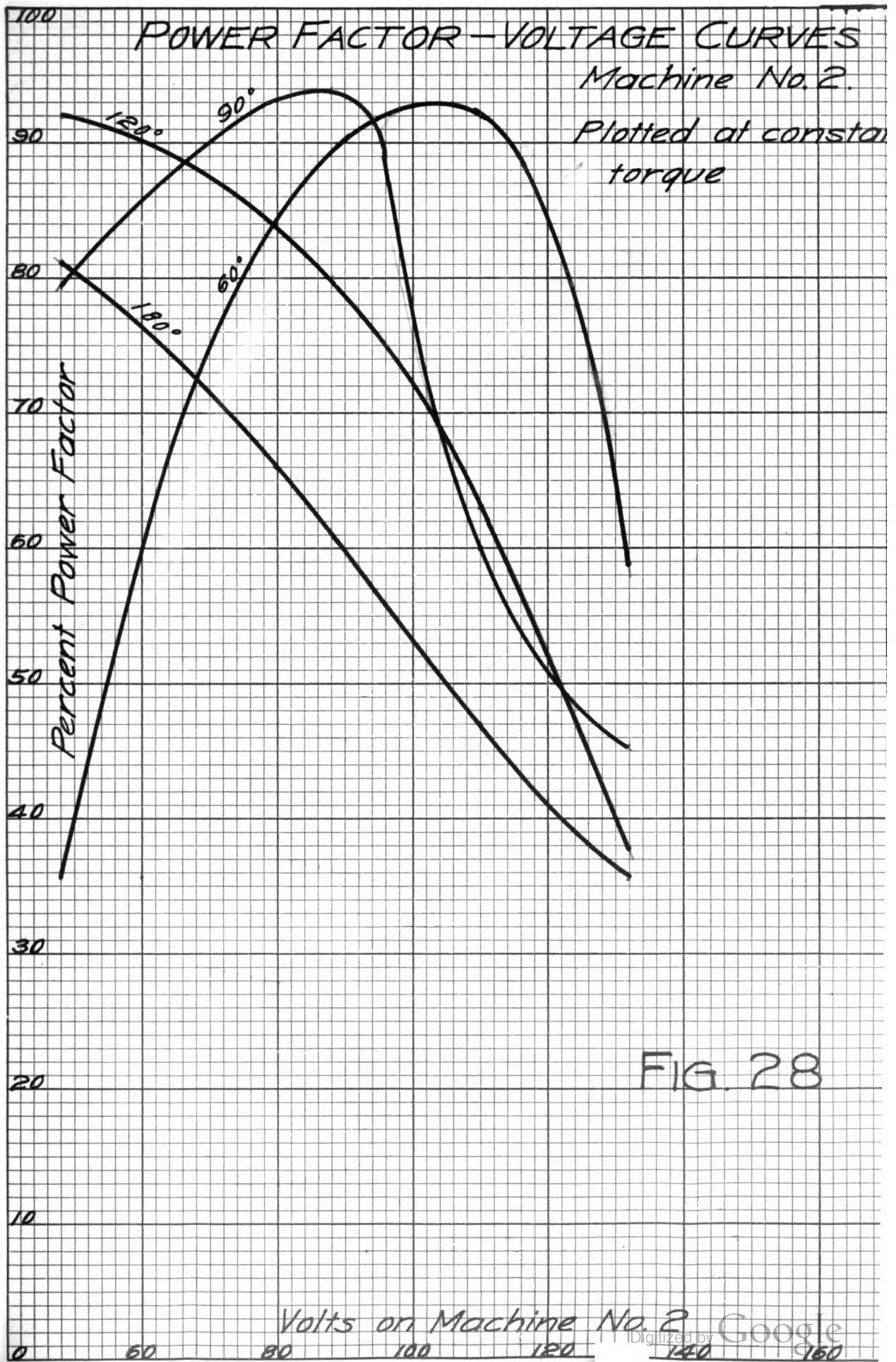












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